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DESIGN OF EQUIPMENT TO OPTIMIZE RELIABILITY FOR MANUFACTURER'S and CUSTOMER'S MINIMUM TOTAL COST

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TABLE OF CONTENTS

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by

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ABSTRACT

For a class of pumps used commercially and aboard aircraft carriers, there exists an optimum level of reliability at which the total cost of this pump to the user is minimum. The reliability of these pumps is predicted and also calculated from field performance data. Actual manufacturer's and customer's cost data are developed, consisting of the manufacturer's cost before and after shipment and his profit, and the customer's cost of buying and maintaining these pumps including downtime cost. From a combined plot of this data, the optimum level of reliability to which the pump should be designed and manufactured is determined for both the manufacturer and the customer. A customer's purchasing philosophy should consider purchasing a product at this optimum level of reliability. Consequently the purchase should be neither at low initial engineering and manufacturing cost, which generally correspond to low reliability and high support cost; nor at very high reliability which corresponds to very high initial cost. In both cases the total cost of the product to the customer is higher than that at optimum reliability, assuming that the total monetary outlay over the life of the product is the major consideration.

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INTRODUCTION - PRODUCT PROCUREMENT PHILOSOPHY

Generally, two basic philosophies have been used by the purchaser of products heretofore. One is to buy at the lowest selling price and the other is to buy the product at the highest possible reliability level. Neither philosophy is correct, because they both lead to a higher total cost of the product over its useful life. We believe that total monetary outlay over the life of the equipment by the user is the primary criterion to be used in the procurement or specification of a product, rather than purchase price alone.

Minimizing this total cost maximizes the utilization of available money and enables the acquisition of more units for the same money. For a given number of required units it minimizes the monetary burden on the taxpayer who after all is the source of our defense budget.

This study establishes the fact that there is such a level of reliability at which the total cost over the life of a specific product is minimum. This level of reliability is called the optimum level of reliability.

The objective of this paper is to develop the relationship between reliability and the manufacturer's and customer's total cost. This is shown first qualitatively and then quantitatively for one product, a pump used by the Navy. It is hoped that proving the existence of such an optimum level of reliability shall stimulate a serious reappraisal of manufacturers' design, manufacturing and purchasing philosophies and practices, and of customers' procurement philosophies.

The philosophy should not be that minimum purchase price nor maximum attainable reliability governs the procurement decision but that the optimum level of reliability does. Furthermore, procurement should be from that manufacturer who supplies a product whose total cost is minimum rather than initial purchase price. If this criterion is met by more than one manufacturer then the successful bidder should be selected on the basis of additional factors such as maintainability, availability, delivery time, etc.

It should be emphasized that the determination of this total minimum cost requires knowledge of the reliability of the product involved and explicitly its "bath-tub" curve.

BACKGROUND - PRIOR STUDIES

Several investigators have developed the concept that an optimum reliability level does exist for certain cost considerations. We feel that Figures 1 and 2 are the first attempts at developing a complete cost picture. Ryerson (1)* and RCA (2) developed the optimum reliability point for the minimum customer's total cost by adding together two reliability versus cost curves. One curve which increases with reliability represents the initial cost to the customer. The other curve which decreases with increasing reliability represents the support cost. The sum of these curves is similar to Curve C, Figure 2 designated as "Customer's Total Cost". These two studies do not consider the manufacturer's total cost picture and no actual cost data in support of these curves are provided.

The existence of an optimum quality for the manufacturer has been pointed out by Delco-Remy (3). This was done by considering the decreasing cost of scrap, reoperation, and warranty as quality increases, plus the increasing cost of a program to achieve increasing levels of quality. The result is similar to the "Manufacturer's Total Cost" shown in Figure 1, Curve C. This study does not consider the customer's total cost picture. We believe that reliability versus cost results in a more useful comparison than quality versus cost because reliability is a precisely defined scientific entity and includes the effect of variable quality.

Other work done by RCA (2), Delco-Remy (3), Winlund (4), Welker and Bradley (5), and Bosinoff (6), has resulted in the enumeration of some of the costs that must be considered to optimize reliability from both the manufacturer's and customer's point of view.

Miller (7), Carhart and Herd (8), Niles (9), Gyllenhaal and Robinson (10), Kalbach (11), Price (12), and Cox and Harter (13) have developed mathematical reliability versus cost models, however, the major obstacle faced in applying these has been the lack of adequate data. One of the objectives of this study is to develop the required data for a specific product and motivate the acquisition of data for cost optimization with regard to reliability in general.

Recently the philosophy that there is an optimum product reliability at which its total cost is a minimum has been extended to the possibilities of lowering this minimum cost and

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* Numbers in parentheses refer to those in the Bibliography.

at the same time increasing the product reliability through the use of an integrated, aggressive and scientifically applied reliability program (1), (2) and (14). This is a very promising extension and should be the subject of other studies.

To date very few studies have been conducted wherein reliability versus manufacturer's and customer's cost curves were developed based on actual reliability and cost data. Cox and Harter (13) have developed curves between the reliability improvement effort and the reliability resulting from this effort for one shot devices. Stevens (15) has demonstrated that reliability improvement costs for electronic subsystems for military aircraft are far offset by maintenance cost savings based on actual cost figures. McLaughlin and Voegthen (16) have determined the support cost of special purpose and waveguide tubes in prime search radar and navigation aid and UHF communication at four Air Control and Warning sites located within the Central Air Defense Force Command. Forty percent of the maintenance hours were found to be required to maintain these tubes. It is concluded that the development of improved parts are most urgently needed to reduce the heavy burden of support and that the present practice of considering only unit purchase price of equipment is misleading. We must determine means of basing development and production decisions on the total cost of equipment for service life.

Bazovsky, MacFarlane and Wunderman (17) present an excellent mathematical analysis of the relationship between reliability and maintenance costs. They developed generalized mathematical linear and non-linear cost models for single components and also for complex equipment. They calculate the failure rates, the number of unscheduled and preventive maintenance actions, part wearout life, time between failures, maintenance time, part replacements, and costs of repair maintenance, preventive maintenance and the resulting total maintenance cost. In doing this they establish optimum reliability levels to minimize the total maintenance cost of a steam turbopump aboard a BuShips surface ship. They feel handicapped in applying their theory in its totality because of lack of sufficient high confidence level operating, reliability, maintenance and cost data.

Bracha (18) presents a comprehensive survey of papers and studies on the effect of unreliability on the support and maintenance costs. The survey shows clearly that such costs can be as high as twelve times the purchase price per year of the original equipment. He emphasizes that attainment of optimum reliabilities is paramount to save the taxpayer money on space and defense projects. He urges that short-range procurement policies should be replaced by long-range planning which considers the total system cost. This cost would include the cost of developing, procuring, and maintaining the entire system in which the equipment is operating. When studies show that the total cost of the system during its useful life would be less by spending more on the initial achievement of reliability and maintainability then the greater initial expenditure is worthwhile.

This study is one of the first major efforts in this field, whereby actual reliability and cost data are used to draw conclusions on the reliability versus total-cost picture of a non-electric product, a Navy centrifugal pump. It is hoped that the investigators quoted previously may welcome the results presented and use the reliability-cost data to further substantiate their theories and findings on reliability-cost optimimization.

MANUFACTURER' RELIABILITY VERSUS TOTAL PRODUCT COST PICTURE

The manufacturer's costs may be simply divided into two major categories:

1. Cost before shipment.
2. Cost after shipment.

The cost for a pump before shipment consists of the following:

1. Direct materials and purchased components.
2. Direct labor.
3. Manufacturing burden.
4. Research and development.
5. Engineering expense.
6. Engineering changes during manufacturing.
7. New patterns.
8. Small tools.
9. Shipping expense - packing.
10. Sales.
11. General and administrative.
12. Miscellaneous.

The cost after shipment consists of the following:

1. Warranty.
2. Good will.

As the reliability of a product is increased, the before shipment cost would also increase as shown in Curve A of Figure 1. It is clear that higher reliability requires the use of better materials, slightly higher cost, more reliable purchased components, the expenditure of more research, development and engineering money. The same would hold for the remaining items, as more stringent controls, better tools, improved packaging, more surveillance and data feedback from the field and the customer would generally be required. These costs would increase slowly with increasing reliability but increase sharply as relatively high reliability levels are sought, particularly when improvement in the state of the art is involved.

The after shipment costs consist of the cost of (a) parts, subsystems and systems for inwarranty failures, (b) service shop charges, (c) travel expense, and (d) other service efforts. These costs are frequently the result of inadequate or improper engineering, manufacturing, sales, purchasing, materials, quality control, inspection or service. In addition, misapplication, incorrect specifications, improper shipping practices, improper erection and startup procedures contribute to warranty costs.

Good will costs are incurred when the responsibility for a failure, malfunction or discrepancy cannot be ascribed clearly to either the producer or the customer and the producer absorbs part or all of the cost resulting from any corrective action.

As the reliability of a product is increased, failures decrease and so would the parts replacement cost, secondary failure cost, and the cost of the rest of the warranty items. At low levels of reliability these costs decrease sharply with increasing reliability and decrease gradually at high levels of reliability, thus giving rise to Curve B in Figure 1.

The sum of Curves A and B gives the manufacturer's total cost, Curve C in Figure 1. To this a profit is added and, assuming a given percent profit, Curve D, the Manufacturer's Selling Price, would be obtained.

A very important observation may be made for Curve D where a minimum selling price at a specific level of reliability, R_{OM}, exists. This level of reliability is known as the optimum level of reliability for the manufacturer. It is interesting to note that any deviation in either direction from this optimum reliability level results in increased cost to the manufacturer. A lower level of reliability results in higher costs because of higher after shipment costs, whereas a higher level results again in higher cost because of higher before shipment costs.

CUSTOMER'S RELIABILITY VERSUS TOTAL PRODUCT COST PICTURE

The customer's cost consists of his purchase price and the cost of operation and maintenance during the life of the product. The latter cost is composed of the following:

1. Maintenance materials and supplies.
2. Maintenance labor.
3. Parts replacement not covered by warranty.
4. Downtime due to malfunction and discrepant performance.

Generally, as the designed-in reliability of a product increases, the customer cost decreases because of a lower failure rate. Consequently, the fewer failures require less replacement parts and maintenance materials and supplies. This will produce Curve A in Figure 2 which represents the cost of unscheduled repairs.

The customer could also have scheduled repair costs. These costs can increase or decrease with increasing product reliability as shown in the following discussion. It is assumed that the period between scheduled repairs remains constant. The scheduled repair cost will decrease if fewer parts are required as the product reliability increases. This case, shown by Curve B, Figure 2, could occur if the parts lives were increased greatly when the product reliability is increased. The second case occurs if approximately the same parts are always replaced during scheduled repairs but the parts costs increase as the product reliability is increased. No curve is shown for this case.

For practical purposes, the operating overhead, installation and procurement costs may be considered independent of reliability. Consequently, they do not affect the trend of the customer's support cost but only shift the level of Curve C upward.

The customer's total costs will obviously be the sum of the initial purchase price plus the support cost over the life of the equipment. Curve C in Figure 2 is obtained by summing Curves A, B and the initial purchase price curve. It is important to observe that Curve C provides an optimum level of reliability, R_{OC}, to the customer at which the total cost of the product to him is minimum. Furthermore, Curve C shows that any shift of useful life reliability from the optimum level increases the total cost. A shift to lower reliability results in higher support costs as well as higher purchase price, and a shift to a higher level of reliability will result in an increase in purchase price greater than the reduction of support costs. It can also be seen from Figure 2 that the total cost will change, depending upon T, the period between scheduled repairs. Therefore, to truly optimize the total costs, both the "designed-in" reliability and the preventive maintenance program must be considered.

It is obvious that there is a shift in the optimum reliability level from that of the manufacturer's to that of the customer's. The competitive and profit picture would influence the decision as to which of these two optimum levels of reliability should be achieved by the manufacturer. It is also quite clear that every product should be designed, built, operated and maintained to obtain this optimum range of reliability. Considerable effort is required to reach this optimum and even when obtained, it will remain a never ending challenge to stay within this range of reliability.

Repair costs are a function of both random and wearout failure rates (22). Also, the scheduled repair cost is a function of four variables.

1. The frequency of the scheduled repairs.
2. The number of parts replaced during each repair.
3. The cost of the parts.
4. The time to make the repair.

The operational reliability of a product which exhibits wearout is dependent upon the interval between scheduled repairs or preventive maintenance actions noted as T. As T is increased more and more unscheduled part replacements will be made due to part wearout and equipment reliability will decrease. The limiting point occurs with no preventive maintenance. The failure rate of the product is then the reciprocal of the product's mean life plus the chance failure rate if all parts are replaced as they fail which gives a mix of part ages. As preventive maintenance actions are performed at more frequent intervals the part wearouts become fewer until only random failures are occurring. Preventive maintenance does not change the random failure rate. Therefore, the reliability of a product with a designed-in failure rate of λ_c can have a range of operational failure rates from λ_c, with a frequent preventive maintenance action, to the wearout failure rate of the product, $\lambda_c+\lambda_w$, which will occur with no preventive maintenance.

Figure 2 shows in three dimensions the relationship between customer cost, useful life reliability and the period between preventive maintenance actions, T.

As T is decreased, the repair maintenance cost decreases because there will be fewer wearouts. But the preventive maintenance cost may increase or decrease, depending upon whether or not fewer parts and less labor are required with the more frequent preventive maintenance actions. These possible changes in costs are shown in Figure 2 by points L and L'; and M and M' or M".

Since the objective of this study is to consider the effect of the designed-in or useful life reliability of a product on its total cost the period between preventive maintenance should be maintained constant at the valve T_1 prescribed by the manufacturer. Therefore, the cost-useful life reliability plane at $T = T_1$ in Figure 2 is the one of interest.

PRODUCT USED TO DETERMINE THE OPTIMUM RELIABILITY VERSUS THE TOTAL COST PICTURE

To optimize reliability with respect to total cost for a product, a product had to be selected that over its production history had undergone several changes that affected its level of reliability. These changes may consist of the following:

1. Design.
2. Material.
3. Purchased components.
4. Manufacturing techniques and processes.
5. Tools and skills.

After a careful investigation it was decided that a product that met the above requirements, was relatively simple in nature and also was used by the Navy was a centrifugal pump. From among the various types and sizes supplied to the Navy, Allis-Chalmers 5" x 4" KSK and SK pumps, illustrated in Figures 3 and 4 were chosen. These pumps have horizontally split casing and a double suction impeller with a specific speed of approximately 1000. The Type SK pump is the basic model dating back to 1933 and the Type KSK is a redesigned model dating back to 1955.

For adequacy of design, cost and sales data, it was decided to confine the study to those pumps sold during the period of 1953 through May 1962.

Design and material changes made in these pumps during this period are given in Table I.

Purchased component changes consisted of bearings, packings, and mechanical seals. Only minor changes were made in manufacturing techniques, processes, tools and skills.

Application environments of these pumps are given in Table II. These environments refer to the internal pump environment and affect the pump component and pump failure rate.

The operating environments of these pumps basically consisted of ground use by industry and shipboard use on aircraft carriers by BuShips. They are broken down in more detail in Table III.

PRELIMINARY PUMP GROUPINGS

The pumps selected for study were broken down into groups which reflected the changes in Table I. These groups essentially represent the coordinates to be plotted on the total cost versus reliability curve. The primary changes which fashioned the preliminary grouping of the pumps are outlined in the following:

1. Shaft diameter was changed from 1.468" to 1.687", thus increasing the strength of the shaft.

2. Higher strength materials like stainless steel and Ni-Cu alloy were used for shaft, shaft sleeves and impeller.

3. Two types of fittings were used:

   a. Bronze
   b. Cast iron

   (The components, shaft sleeves, casing bushings, shaft nuts, casing rings and impeller are of bronze in the case of bronze fitted pumps and are of cast iron in the case of cast iron fitted pumps.)

4. Four different types of bearings:

   a. "B1G" - ball bearing with one row of balls, grease lubricated.

   b. "B1O" - ball bearing with one row of balls, oil lubricated.

   c. SB - sleeve type bearings.

   d. "B2G2" - ball bearing with two rows of balls side by side and grease lubricated.

Two other important variables considered were impeller diameter and width. The effects of these two variables on pump head, radial load on the shaft and the bearings, bearing thrust load and pump brake horsepower are discussed under "Combined Pump Stress Analysis".

On the basis of above criteria, the pumps in this study were carefully studied and were divided into eighteen (18) preliminary groups.

DATA SOURCES AND ACQUISITION

The acquisition of the required basic pump performance reliability data was as follows:

1. From the Allis-Chalmers Fluid Dynamics Department the serial numbers of all pumps in the eighteen preliminary pump groupings were tabulated showing the information required to fill the upper portion of the form in Figure 5.

2. The form in Figure 5 was filled out and sent to Allis-Chalmers District Offices through which the pumps were sold. The District Offices requested that the commercial customer complete the form and return it. If after a prescribed time the forms were not received, a follow-up letter was sent out. In total 276 forms were sent out to commercial customers, of which 104 were returned filled out adequately, or 38%.

3. The serial numbers of pumps which had been sold to the Navy were grouped according to aircraft carriers on which they were installed. Letters were written through Lt. Commander Art Coyle, Power Branch, ONR, to the Commanders of the Pacific and Atlantic Fleets requesting that the Captains in command of the aircraft carriers have the form in Figure 5 completed, and furthermore, supply Allis-Chalmers with a copy of their Machinery History Card, NAVSHIP 527 (Rev. 10-48), as shown in Figure 6. Out of 151 pumps aboard Navy vessels information on 117 pumps was received or 78%. The outstanding cooperation of the carrier personnel in supplying us copies of their Machinery History Cards should be commended, as this information has enabled us to develop a bathtub curve for the fire pumps used aboard aircraft carriers. Data on the remaining pumps could not be obtained because either the vessels were at sea during the Cuban quarantine of the Fall of 1962 or vessels with pumps aboard were still under construction.

4. The Bureau of Ships, Code 706A, performed a search of their compilation of Reports of Equipment Failure, Form NAVSHIPS 3621 (Rev. 6-59) shown in Figure 7 to obtain the total number of reported failures for the period under study.

5. The Fluid Dynamics Department Renewal Parts file was searched for repair parts and date of order for all pumps sold commercially. This data was used to supplement the information received on the Centrifugal Pump Reliability Report.

The acquisition of the required basic pump cost data was as follows:

1. Works Accounting Department of the Allis-Chalmers Comptroller's Division supplied the pump specification cost. This cost was available directly from the original order forms and tickets and includes direct labor, materials, purchased components, and manufacturing burden.

2. The cost of research and development, net engineering, engineering changes during manufacturing, new patterns, small tools, shipping expense and certain miscellaneous items was obtained from the Accounting Department for all pumps built. These are accumulated for all company products on a product line basis and cannot be isolated for a specific model in that product line. Using the experience and judgment of personnel in areas where these costs are originated, the costs accumulated for the product line were apportioned to the pump groups under study.

3. The after shipment manufacturer's cost consisting of warranty and good will costs are compiled under a separate account at Allis-Chalmers. These were extracted by the Accounting Department for all the serial number pumps making up the groupings.

4. The customer support cost was determined as follows:

   (a) All parts replaced on the pump were requested to be entered on the Centrifugal Pump Reliability Report by the customer. These parts were then extracted from the reports for each group.

   (b) Costs of the replacement parts were provided by the Renewal Parts Section of The Allis-Chalmers Fluid Dynamics Department.

   (c) Hours to repair or replace each part entered on the Centrifugal Pump Reliability Report were found by using a teardown and assembly time chart or accessibility tree obtained from the Timestudy Section of the Allis-Chalmers Manufacturing Planning Dept. They were complemented by values from the Pump Repair Section and the Service and Renewal Parts Section of the Fluid Dynamics Department.

(d) Downtime costs per hour to the customer were requested on the Centrifugal Pump Reliability report and ten customers responded. These are costs resulting from loss of production and stoppage of surrounding equipment. The product of the downtime cost per hour and the total pump repair time gave the downtime cost per group.

FINAL PUMP GROUPINGS

Due to insufficient data, evidenced by lack of customer report and/or hours of operation, to establish a reasonable confidence level in the calculated failure rates the pump groupings had to be changed. More specifically the changes are shown in Table IV and are discussed in the following:

Groups 1*, 2 and 3 were reapportioned into Groups I and II.

Groups 4, 5, 6 were regrouped as Groups III and IV.

Groups 7 and 8 returns were inadequate and those obtained could not be merged with the closest group, Group I, because of differences in casing and shaft sleeve material, higher discharge pressure flanges and the presence of an outside seal.

Group 9 was eliminated specifically because six of the seven pumps originally comprising this group were shipped to Puerto Rico and no reply to our reliability form was received. The one pump reported upon in Group 9 could not be combined with any other group because it is the only pump with sleeve bearings.

Group 10 was omitted since only 2000 hours of operation were accumulated on the nine pumps comprising the group.

Groups 11 and 12, which are Navy fire and catapult water brake pumps respectively, and had the most abundant returns were renumbered as Groups V and VI.

Group 13 consists of Navy jet fuel pumps aboard an aircraft carrier. However, inadequate data was provided and this group was deleted.

Group 14 consisted of stainless steel fabricated pumps sold to one company which had gone out of business.

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*Note: The original groupings are numbered in Arabic numbers while the final groupings are numbered in Roman numerals.

Groups 15, 16, and 17 were merged and resplit into two groups, VII and VIII, to provide more population in each group.

Group 18 was deleted since the owners did not provide any reliability data although the entire group was sold on two orders.

The new and final eight (8) groupings are given in Table IV with the corresponding preliminary groupings and in Table V with the number of pumps in each group and the comparative differences between groups. In addition the following paragraphs describe a representative pump in each group.

Group I:

A bronze fitted pump having a small diameter shaft (D = 1.467") of SAE 1045 annealed steel, "BlG" bearings, bronze impeller with a diameter ranging from 7.0" to 9.0" for a wide outlet and from 7.0" to 9.5" for a narrow outlet, cast iron casing, standard packing of soft asbestos and standard seal.

Group II:

A bronze fitted pump having a small diameter shaft (D = 1.467") of SAE 1045 annealed steel, "BlG" bearings, bronze impeller with diameters ranging from 9.0" to 11.0" for a wide outlet and from 9.5" to 11.0" for a narrow outlet, cast iron casing, standard packing of soft asbestos and standard seal.

Group III:

A bronze fitted pump having a large diameter shaft (D = 1.687") of SAE 1045 annealed steel, "BlG" bearings, bronze impeller with diameters ranging from 7" to 9.0" for a wide outlet and from 7" to 9.5" for a narrow outlet, cast iron casing, standard packing of soft asbestos and standard seal.

Group IV:

A bronze fitted pump having a large diameter shaft (D = 1.687") of SAE 1045 annealed steel, "BlG" bearings, bronze impeller with diameters ranging from 9.0" to 11.0" for a wide outlet and from 9.5" to 11.0" for a narrow outlet, cast iron casing, standard packing of soft asbestos and standard seal.

Group V:

Assembled with a large diameter tapered shaft (D - 1.687") of Ni-Cu alloy, "B2G2" bearings, wide outlet Ni-Cu alloy impeller with a diameter of 10-1/8", gun metal casing, Fleximetallic packing and gun metal seal cage.

Group VI:

Assembled with a large diameter tapered shaft (C = 1.687") of steel, "B2G2" bearings, wide outlet Ni-Cu alloy impeller with diameters ranging from 7" to 8.47", gun metal casing, Fleximetallic packing and gun metal seal cage.

Group VII:

A bronze fitted pump having a large diameter shaft (D = 1.687") of SAE 1C45 steel, "B1G" bearings, bronze impeller with diameters ranging from 7" to 9.0" for a wide outlet and from 7" to 9.5" for a narrow outlet, cast iron casing, standard packing of soft asbestos, standard wearing rings with a snap ring bearing retainer.

Group VIII:

A bronze fitted pump having a large diameter shaft (D - 1.687") of SAE 1045 steel, "B1G" bearings, bronze impeller with diameters ranging from 9.0" to 11.0" for a wide outlet and from 9.5" to 11.0" for a narrow outlet, cast iron casing, standard packing of soft asbestos, standard wearing rings with a snap ring bearing retainer.

COMBINED PUMP STRESS ANALYSIS

As can be seen by the description of the final groupings Groups I and II, III and IV, and VII and VIII are similar. The difference is that the first group in each case has a smaller range of impeller diameters. The division of impeller diameters is 9.0" for wide (15/16" opening width) outlet impeller, 9.5" for the narrow (3/4" opening width) outlet impellers. This division was arrived at by employing a general stress analysis of the pump groups. The results are used to determine certain failure rate modifiers for the pump reliability prediction. It should be emphasized that the analysis presented herein is not meant to be a rigorous fibre stress analysis. Instead comparative equations are introduced to obtain a measure of the general pump stress levels involved, and rank the pump groups accordingly.

Stress analysis involved determining the relative effect of increasing the impeller diameter, changing from wide to narrow impeller widths, and changing discharge pressures; on the stress level of the two sizes of shafts and the two bearing configurations which remained in the final groups.

The governing criteria of shaft failure is the maximum shear stress imposed upon the material. The equation for this stress is:

$$\text{Maximum Shear Stress} = 1/2 \left[\left(K_m \frac{M_C}{I}\right)^2 + 4\left(K_T \frac{T_C}{J}\right)^2 \right]^{\frac{1}{2}}$$

where K_m and K_T are variable and impact load factors and were obtained from Kent's Mechanical Engineers Handbook (19). The Moments of Inertia I and J were determined from the shaft dimensions.

The bending moment, M_c, was determined by the product of one-half the force acting on the impeller discharge and one-half the distance between bearings. The discharge pressures and consequently the force of the impeller discharge is obtained from Figure 8 for narrow impellersand Figure 9 for wide impellers.

The torque Tc, imposed on the shaft can also be found from Figures 8 and 9 for the combination of impeller diameter and width under consideration by converting the brake horsepower requirement to torque.

Figure 10 shows the relative shaft stress for all the groups. A factor of 2/3 times the stress curve for a large steel shaft gives the stress curve for monel since it has a yield strength 50% higher than that of steel.

In determining bearing stress both the radial and thrust loads were found. The radial load, L_R, is a function of the impeller width, W, and diameter, D, as may be seen from the following:

$$L_R = K_1 HA$$

where K_1 is a constant characteristic of a pump and its specific speed,
H is the pump head, and
A is the projected area

Since H is proportional to the impeller diameter squared, D^2, and A is equal to impeller diameter, D, times the impeller width, W, the following ratio results for two similar pumps.

$$\text{Relative Radial Load} = \frac{W_1 D_1{}^3 N_2}{W_2 D_2{}^3 N_1}$$

where N is the number of bearings on each end of the shaft.

Similarly, the thrust load on the bearing is determined for the number of rows of balls in the bearing, N, by

$$\text{Thrust Load} = K_2 H \quad (D^2 - d^2) \quad (\frac{1}{N})$$

where d = shaft diameter

Substituting for H and forming a ratio we obtain an equation applicable to two similar pumps,

$$\text{Relative Thrust Load} = \frac{(D_1{}^2 - d_1{}^2) D_1{}^2 N_2}{(D_2{}^2 - d_2{}^2) D_2{}^2 N_1}$$

The computed relative bearing radial end thrust loads are given in Figure 11 for all groups.

The combined pump stress, shaft and bearing, as a function of impeller diameter was found by adding the appropriate curves in Figures 10 and 11. Since the failure rates of the bearings and shaft would be added together in obtaining the pump failure rate, and furthermore, since failure rate is a function of stress, or load in the case of bearings, the following equations are obtained as a measure of the combined pump stress:

$$\begin{aligned} A + F + E &= J \\ C + F + E &= K \\ B + G + E &= L \\ D + G + E &= M \\ 2C/3 + I + H &= N \\ C + I + H &= P \end{aligned}$$

where the letters to the left of the equality sign refer to the curves in Figures 10 and 11, and the letters on the right to the curves in Figure 12. In Figure 12 it can be seen that the relative stress level for pumps with "B1G" bearings and wide impellers is divided approximately in two at an impeller diameter of 9.0", and at 9.5" impeller diameter for pumps with "B1G" bearings and narrow impellers diameters. This is indicated by the horizontal dotted line. It was not necessary to divide the remaining pump groups up since their combined stresses were distributed over narrow impeller ranges.

The limiting stress values for each group in Figure 12 are shown by bars in Figure 13.

PREDICTED PUMP RELIABILITY

Prediction of the reliability of each pump group was required so that (1) a cross check on the actual field failure rates could be made to determine if unusual situations had significantly affected the data, and (2) modifiers could be developed to enable normalization of actual field data to a comparable environment.

The predictions were made under the assumption that the pumps would exhibit a constant failure rate, that all pump elements were in series reliabilitywise and that the part failure rates were independent of each other.

The basis of this reliability prediction is the part generic failure rate. It is defined as the inherent failures per million hours of operation that will occur on a part or unit which is operated in a laboratory environment. The generic failure rate applies to the conditions of no externally applied vibration or shock. It also assumes, in the case of pumps, that pure water is being pumped, at continuous operation, within the most efficient operating range of the pump and that the water and surrounding air are at ambient temperatures. The generic conditions also assume perfect alignment of the pump and its driving motor so that the motor is not contributing to any stress risers within the pump.

A listing of pump components and their generic failure rates is given in Table VI. These generic rates, slightly adjusted according to our knowledge of the parts and their use in these pumps, were obtained from Earles (21). Nonexisting generic failure rates were developed by modifying those of a similar part by engineering judgment. Generally, three or four engineers were asked to come up with failure rates for parts on which no data was available; these were then weighed according to the level of experience of the engineer and averaged to establish the accepted failure rate appearing in Table VI. These generic part failure rates were summed for all components of a pump in each group to obtain the generic pump failure rate. These values are tabulated in Table VI and Table XII. The totals in Table VI were arrived at by first summing up the failure rates of all components common to all pumps. Then the sum of the failure rates of the parts peculiar to each group were added to the value for the common parts to obtain the generic failure rate of each group.

After the generic failure rates were thus established, the predicted field failure rates were developed. Two factors were developed which modify the generic failure rate to meet the environmental conditions which the field pump experiences. The Application Factor, K_A and the Operating Mode Factor, K_{OP}, take into consideration the internal and external environments of each pump.

In addition, a factor is required for each pump group which will indicate the over-all level of reliability, design improvements, or state of development of the pump which was not accounted for in the part failure rates. This factor is called the Design Group Factor, K_G.

Application Factor

The Application Factor was developed from engineering knowledge of the effect of the environment on the materials used in the pump groupings. Table VII shows application factors for all the application environments the pumps encountered. The base value of K_A=1 is for the pump pumping pure water. These application factors were applied to each pump as follows:

A non-corrosive pump operating in brine at 16-35% variation would have a K_A=3.5 x 1.1=3.85. Table VIII gives the average application factor for each one of the eight pump groupings.

Operating Factor

Operating environments such as vibration, acceleration, and shock affect the failure rate of the packing, bearings and other pump parts. Hence, to predict the actual field failure rates the Operating Factor - K_{OP} - was developed to obtain the failure rate in the actual operating environments. This is done by multiplying the respective generic failure rates by K_{OP}.

Earles (21) has given an "S curve" (Figure 7, p. 391 in reference 21) showing mean K_{OP} factors for different equipment installations. But he did not show the deviation about the mean K_{OP} for different degrees of severity in operating environments.

The mean K_{OP} and its standard deviation was determined by using Earles' data which appear in Figure 14. It was assumed that the logarithms of the failure rate data presented in this figure would give approximately a normal distribution. Therefore, a normal distribution curve for each one of the three installation environments, laboratory, ground, and shipboard, was fitted to these data points. For these distributions the following quantities were obtained.

Laboratory: Mean K_{OP} = 0.928
Standard deviation (σ) = 5.0
Logarithm σ = 0.7
3 σ limit (upper) = 135.2
3 σ limit (lower) = 0.01176

Ground: Mean K_{OP} = 9.45
Standard deviation (σ) = 3.5
Logarithm σ = 0.548
3 σ limit (upper) = 415.9
3 σ limit (lower) = 0.214

Shipboard: Mean K_{OP} = 18.8
Standard deviation (σ) = 3.0
Logarithm σ = 0.48
3 σ limit (upper) = 512.7
3σ limit (lower) = 0.677

From the foregoing it may be seen that the ratio of the mean ground failure rate to the mean laboratory failure rate is 10.2, whereas the ratio of the shipboard to the laboratory mean failure rate is 20.2. These values verify the Operating Factors given by Earles (21).

The operating environments found from the field data were studied carefully and it was decided that the variation in K_{OP} could not be between $\pm$ 3 σ or $\pm$ 2 σ limits but would most likely lie within $\pm$ 1 σ limits based on the following discussion.

Data presented in Figure 14 was obtained from 30 different projects and 500 different components. These 500 components include components of various types of equipment including electronics, electrical, mechanical, hydraulic, etc. With this wide spectrum of equipment types the calculated $\pm$ 3 σ limits given above were obtained. However, when one type of equipment such as centrifugal pump is considered, the magnitude of the deviation range would be much smaller. It is estimated that $\pm$ 1 σ deviation of the total equipment population in Figure 14 in the ground environments would essentially cover a $\pm$ 3 σ deviation for pumps alone in Ground environments.

Knowing that the range of variation for the Operating Factor would be in the same proportion as the variation of the failure rates in each installation environment, then the extreme limits of "K_{OP}" for Ground and Shipboard environments may be calculated as follows:

Ground: $$\frac{\text{Min. } \lambda}{\text{Mean } \lambda} = \frac{\bar{x} - \sigma}{\bar{x}} = \frac{9.45-3.5}{9.45} = 0.63$$

$$\frac{\text{Max. } \lambda}{\text{Mean } \lambda} = \frac{\bar{x} + \sigma}{\bar{x}} = \frac{9.45+3.5}{9.45} = 1.37$$

From our experience the "mean K_{OP}" for these pumps in Ground environments is 7.0.

Hence, Min. $K_{OP} = 0.63 \times 7$
$= 4.41$ Say 4.5

Max. $K_{OP} = 1.37 \times 7$
$= 9.59$ Say 9.5

Shipboard:

$$\frac{\text{Min. } \lambda}{\text{Mean } \lambda} = \frac{\overline{x} - \sigma}{\overline{x}} = \frac{18.8-3.0}{18.8} = 0.84$$

$$\frac{\text{Max. } \lambda}{\text{Mean } \lambda} = \frac{\overline{x} + \sigma}{\overline{x}} = \frac{19.8 + 3.0}{} = 1.16$$

$$\text{Mean } K_{OP} = \frac{20}{10} \times 7 = 14.0$$

(Mean values of "K_{OP}" estimated by Earles are: Ground = 10, Shipboard = 20)

Hence, Min. $K_{OP} = 0.84 \times 14$
$= 11.76$ Say 12.0

Max. $K_{OP} = 1.16 \times 14$
$= 16.24$ Say 16.0

After establishing the range of K_{OP} for the ground and shipboard environments, the K_{OP} values applicable to the pumps operating in the environments given in Table III were arrived at using engineering judgment as to the relative severity of these environments. These K_{OP} values are given in Table IX. As some of the groups contain pumps that do not have the same operating environment, the respective K_{OP} values of the pumps in each group were averaged and this value used as the one applicable to that group as a whole. The group K_{OP} factors are given in Table VIII.

Design Group Factor

The failure rate of a component changes with improvements in design and with changes in material, e.g., a shaft of larger diameter would have lower failure rate than that of a small diameter shaft under similar application and operating environments. Also, a shaft of higher strength material would have a lower failure rate than the shaft of the same diameter but of lower strength material. Because of this adjustment in failure rate should be made to predict the actual field failure rate from the predicted generic failure rate. Hence, a factor called the Design Group Factor, K_G, was developed.

To develop the Design Group Factor the eight pump groups were classified into six design classes that show the comparative improvement in design and material with respect to one another. The following items were found playing significant roles in the general stress level of the pumps:

1) The shaft diameter was changed from 1.468" to 1.687.
2) Higher strength materials like NiCu alloy were used for the shaft.
3) Two different types of bearings were introduced.
4) A variety of impeller diameters was used.
5) Two impeller widths were used.
6) The date of manufacture of the group and the corresponding effect of modernized technique in manufacture were different among some groups.
7) Some parts such as shaft sleeves and impellers were made from higher strength materials in some groups.
8) The Navy pumps were manufactured to more rigid specifications than commercial pumps.
9) A redesign was made specifically for the purpose of reducing the cost of the basic line of pumps, resulting in the pumps in Groups VII and VIII.

Based on these factors and the results of the combined stresses shown in Figure 13, a ranking of the eight groups, based on relative general stress was established, as shown in Figure 15.

Considerations of the general stress result in the following change from the combined stress values which are shown for each group in Figure 13. Only the pumps in Groups V and VI are in the same position as in Figure 13. Groups I and II were moved up two stress levels on the abscissa or stress axis because these pumps were manufactured earliest and are not in general made up of as many high strength parts as the pumps in Groups V and VI. The pumps in Groups III and IV are better designed than the ones in Groups I and II but not as advanced as pumps in Groups V, VI, so their relative general stress lies between these groups, as shown in Figure 15. Similarly, since the pumps in Groups VII and VIII were redesigned for initial cost cutting purposes and are not as well designed as the ones in Groups III and IV, their relative general stress is above that of these groups. The general stress axis in Figure 15 is divided into six design classes. Table X shows the groups that fall into each design class.

It is mentioned above that each significant change in design affects the failure rate of the pump. Thus, any improvement in the design of any component of the pump which causes a change in its failure rate establishes a definite range between the failure rates of the two designs. As the classification of eight groups into six design classes is based on the improvements in the design of the pump, there is a range between failure rates of the six design classes.

Each component part of a system has mean, maximum, and minimum failure rate. If the mean is considered to be typical of average design, then the maximum failure rate corresponds to a below average design and the minimum failure rate to a better than average design. Thus any change in failure rate due to improvements in design could be represented by one of the following two ratios:

1) Maximum generic failure rate to minimum generic failure rate, and

2) Mean generic failure rate to minimum generic failure rate.

Each of the two ratios has a definite meaning. The first ratio represents the improvement from early design to well developed design, and the second ratio represents the improvement from average developed design to well developed design. These two ratios were calculated for major components and are given in Table XI.

Allis-Chalmers has been manufacturing pumps for several decades and during this period the design has been reviewed many times to introduce new developments to improve pump designs. These improvements are exhibited by the pump groupings. Because of the extensive past history of these pumps, the ratio of maximum generic failure rate to minimum generic failure rate was thought to be too high to use as a representative ratio of the failure rates between classes 0 and 5. Hence, it was decided to use the ratio 2.45 (see Table XI), the ratio of mean generic failure rate to minimum generic failure rate. Thus λ class $5/\lambda$ class $0 = 2.45$, and the ratio of the failure rate of all the design classes to the failure rate of design class 0 can be determined by assuming a linear relationship. These ratios, called E_i are given in Table X.

The ratios in Table X are relative multipliers showing the increase in failure rate for different pump designs. Now, absolute multiplying factors need to be developed. A pump which is representative of today's state of design and development, and is commensurate with industry practice should be assigned a K_G=1. The pumps in Group III are the most logical selection. Hence the K for Group III is 1. The Navy pumps are specially designed pumps and their designs are better than the design of the pump in Group III. Thus, the K_G for the Navy pump groups will be less than 1. The reverse is the case for the remaining groups.

Therefore, the factor K_G for all groups is determined as follows:

$$K_G \text{ for Design Class } 2 = \frac{E_1}{E_2} = \frac{1.29}{1.58} = 0.816$$

The K_G for all other groups was calculated similarly and is given in Table XII.

Predicted Pump Field Failure Rates

The predicted pump field failure rates were calculated by taking the product of the respective group generic failure rates, application factor (K_λ), the operating factor (K_{OP}), and the design group factor (K_G). These factors and the predicted failure rates for each group are all tabulated per group in Table XII.

ACTUAL PUMP RELIABILITY

Actual pump reliability was determined by the analysis of the performance data obtained from the sources discussed in "Data Sources and Acquisition". The basis for analyzing this data is the identification of a reliability failure. Criteria for this identification are discussed next.

Criteria for Field Failure Classification

A relevant reliability pump failure has occurred when a pump ceases to supply the required output or stops for any reason, excluding scheduled operational stops, scheduled maintenance stops or any reason outside the pump, i.e., power failure, damage to pump from outside sources, or the pump being a secondary failure. In addition, for the purpose of this study, excessive noise, leakage and/or vibration constitutes a failure.

All relevant pump failures were classified as wearout and random. Any time dependent failures were classified as wearout and included wear and corrosion. Any time independent failures, in this case, the rest of the relevant failures, were considered as random failures.

The reason for this failure division is that data received from the customer was not detailed enough. Principal source of data was the Centrifugal Pump Reliability Report and Machinery History Cards. In general they were filled out well enough to determine whether or not a repair or replacement was the result of an unscheduled pump stoppage. The Centrifugal Pump Reliability Reports and the Machinery History cards contained several factors which often gave clues to what occurred, such as the language used, the time period between repairs and the type and number of parts replaced.

Parts which wore out at uniform operating intervals, even though of short duration, were not counted as relevant failures, particularly if they occurred on the same ship or installation. In general, a broken part was counted as a relevant failure.

Failures attributed to the drain pipes and their valves on the Navy pumps were not counted since these are parts extraneous to the basic pump.

Wearout of the casing and impeller rings and shaft sleeves are not ordinarily detectable during pump operation. Therefore, wearout will generally be detected only during a maintenance inspection or when another part is being replaced. Such a wearout was not considered to have caused an unscheduled pump outage. However, breakage of these parts was counted as a relevant failure.

Manufacturing errors due to poor workmanship were counted as relevant failures. Field failures which occurred due to incorrect maintenance practices or workmanship were not counted as relevant failures if they were of a repeating type because these were not the result of pump unreliability. Non-repeating failures which were caused by poor workmanship were considered relevant.

Spare parts orders were used as indicative of a pump failure only after the following factors were considered.

1. Time between pump installation and spare parts ordered.

2. Type of parts ordered (parts that are normally replaced as part of maintenance program or others).

3. Number of spare parts ordered.

4. Order specified parts for a breakdown.

5. Orders were so spaced that the interval between orders was a great deal less than the expected wearout life of the components or reasonable preventive maintenance intervals.

By using the above failure criteria, all failure data sources were examined and the reliability failures counted. Failures reported by BuShips, Code 706A on the Report of Equipment Failure, were checked against those counted by examining the Carrier's Machinery History Cards, and all were accounted for. The failures thus obtained for each group are tabulated in Table XIII.

Determination of Hours of Operation

In general the customer reported this by checking the closest value of the average pump operating hours per day on the Centrifugal Pump Reliability Report. However, several customers provided actual hours and also hours between repairs and replacements, as well as checking a box on the questionnaire. From this latter information the following relationship between the checked average operating hours per day and the actual operating hours per year were determined.

4 hrs/day equivalent to 1250 hrs/yr.
8 hrs/day equivalent to 2500 hrs/yr.
16 hrs/day equivalent to 5000 hrs/yr.
24 hrs/day equivalent to 7500 hrs/yr.

Using the above values and the date the pump was put into operation, as stated by the customer, the total pump hours of operation were determined. The results are given in Table XIII for each pump group.

Calculation of Failure Rates

From the failures and hours of operation, the failure rates for all groups except Group V were calculated from:

$$\text{Group Failure Rate} = \frac{\text{Total Failures Occurring for the Group}}{\text{Total Accumulated Hours of Operation by All Pumps in the Group}}$$

The results are given in Table XIII. The failure rate of Group V was determined as follows:

Using the data provided by the Navy for Group V, a reliability "bathtub" curve was constructed. The hours of pump operation accumulated before a failure occurred were not available for all pumps, however. In such cases, they were estimated using the equation given below to determine the operating hours per month. The number of months of service were calculated from the date the pump was placed into service up to October 1, 1962.

$$\frac{\text{Accumulated hours of operation up to Oct. 1, 1962}}{\text{Number of months in service}} = \text{Hours of operation per month of service}$$

Accumulated hours of operation and months of operation before failure were taken from the Centrifugal Pump Reliability Report and/or Machinery History Cards. The product of the hours of operation per month and the months operated before failure gave hours of operation up to the failure.

Maximum total hours of operation accumulated on individual pumps were less than 16,000 hours. This span was divided into 16 equal intervals.

The hours of pump operation and failures which occurred during each interval were determined and are given in Table XIV. The failure rates were calculated using the following equation:

$$\text{Failures}/10^6 \text{ hours} = \frac{\text{No. of failures during the interval}}{\text{Millions of hours of operation accumulated by all pumps during the interval}}$$

Group V - Navy Pump "Bathtub" Curve

A graph of failure rate vs. hours of operation, was plotted giving the reliability bathtub curve of Figure 16. Here the assumption was made that there was immediate replacement after a failure and down time is negligible. Some pumps, though not failed, have operated only part way through an interval because they have not been in service long. This was taken into account in arriving at the total operating hours for the pumps in each interval. Each failure rate point was plotted at the mean of the interval. The graph given as Curve 1, Figure 16, is the actual curve obtained by using field failure rates in Table XIV. Curve 2, on Figure 16, is a uniform mean of failure rates of all intervals excluding those of two extremes. Curve 3 is a step mean. The step mean consists of two parts: (1) between 1,250 to 9,250 hours; and (2) between 9,250 to 14,250 hours. Each portion has its own mean.

These curves may be interpreted as follows:

Curve 1: Between hours 0-1,250 there is a sharp fall in failure rate which may be interpreted as a period of early failures. Then, between hours 1,250-2,750 the failure rate is more or less constant representing random occurring failures during this period. The curve then shows a sharp rise indicating frequent wearout failures of short life components. The rise in failure rate between hours 4,500-6,500 may be due to the wearout failures of those short life components which were replaced during the previous period of frequent wearout. If wornout components are not removed simultaneously, but gradually as they failed, the curve will be considerably flattened, as shown. The curve shows that there is again a steep rise in failure rate at the point where the previous bell shaped curve ends. This forms another bell shaped curve between hours 7,500-8,500. This indicates frequent wearout failure of long life components and also of the short life components which were replaced between hours 2,750-6,500. Failure frequency between hours 10,000-14,500 is constant and indicates that the failures are occurring randomly. The failure reports indicate that the major overhaul was done on most pumps at about 9,000 hours. This may also explain the low failure rate after this period. At the end of this period the curve again rises indicating frequent wearout failures.

Curve 2: It has been already mentioned that the repair and replacement parts reports obtained from the U.S.Navy were not complete. Consequently, the failures were classified according to the rules discussed previously. Thus, the failure rates given in Table XIV are only an estimate of the true failure rates. These rates are subject to statistical error which may be large or small, depending upon the volume of data and its accuracy. By calculating one uniform mean failure rate, these errors are redistributed and a curve is obtained amenable to easier analysis.

Curve 3: Curve 3 was drawn to increase the accuracy of estimating space part provisioning over that of Curve 2 and to approximate points closer by dividing the whole span into two equivalent "bathtub" curves.

Curve 3 could be indicative of two major facts: (1) The ship's operating environment is changing. Perhaps, since these pumps were placed aboard the ship when it was being constructed, the curve indicates that much of the early life of the ship is spent in harbors and as it ages it spends more time at sea. If so, the fire pumps during their early life would be pumping sea water with considerable amounts of sand, because the intakes for the fire pumps are on the bottom of the hull, which would definitely increase the pump's failure rate. As a greater percentage of time is spent at sea, the pump's failure rate would decrease because of the lower content of sand in the sea water. (2) The maintenance practices of the ship's crew improves with time. It is possible that the crews are somewhat inexperienced when the ships are initially put to sea and their maintenance procedures and quality of work is low. However, as time goes by they improve and pumps experience lower failure rates because of the reduction in failures due to misalignment, incorrect torqueing, etc. This assumes, of course, that there is no frequent rotation of crew which brings in a relatively inexperienced crew.

The pump failure rates will be used here as a measure of the pumps' reliability. This is done so because, as reliability is a function of mission time, as well as of failure rate, and the mission time may be different for each group of pumps, it eliminates the variability of mission time. However, knowing the failure rate and selecting an applicable mission time the pumps' reliability may be calculated when the product exhibits a relatively constant failure rate characteristic.

COMPARISON OF PREDICTED VERSUS ACTUAL FIELD FAILURE RATES OF THE PUMPS

To evaluate the pump field failure rate prediction technique developed in this study Figure 17 was prepared where the predicted values are shown alongside the actual field failure rates for all eight pump groups. The predicted values came from Table XII and the actual from Table XIII and Figure 16.

The maximum, mean and minimum pump failure rates, given in Table XII, are related in general to the state-of-the-art in the following manner:

The maximum failure rate corresponds to a pump which is in an early state of development, the mean failure rate to an average developed pump, and the minimum to a pump with an advanced design. By examination of Figure 17 it can be seen that the 5 x 4 SK and KSK pumps are all well designed pumps for the environments they are operating in because the actual pump failure rates are quite close to the minimum predicted. This is not surprising since these pumps are the evolution of a pump which was initially designed in 1913. However, today a design must be developed much quicker and the key to our ability to speed up design is an active reliability program with data feed back and a corrective action program.

Figure 17 bears out the fact that the combinations of the generic failure rate, application factor (Ka), operating factor, (K_{OP}), and the design group factor (K_G) were chosen well since the actual failure rate is quite close to the minimum predicted. In addition it may be seen that the ranking of actual failure rates was predicted almost perfectly. From this it can be concluded that failure rate prediction can be a very valuable and extremely useful tool.

It also is apparent that the Navy pumps correspond to the advanced state-of-the-art. This was predicted while developing the Design Group Factor (K_G).

It is obvious from Figure 17 that there is a wide band between the mean and minimum predicted field failure rates. Up to this time little work has been done on the reliability of mechanical systems and because of this the generic failure rates available for mechanical components may not be precise. Also, generic failure rates were not available for all mechanical components of the pumps and hence were estimated by using proper engineering judgment. Any error in the estimations will be reflected in the predictions. As time goes on and more work is done on the reliability of mechanical systems, failure rates for more mechanical components will become available, which will help improve prediction techniques.

Predicted failure rates and the use of the multiplying factors, K_A, K_{OP}, and K_G were based on the assumption that the pump would exhibit a constant failure rate. As shown by Figure 16, this assumption is a close approximation where the overlapping wearout distributions of the individual components sum up to form a relatively constant failure rate curve (22). Therefore, based on Figure 16 a constant failure rate can be assumed for all pumps in this study.

MANUFACTURER'S TOTAL COST

To show the reliability versus cost picture in a logical manner, it is necessary to reduce the cost figures to a base year to present unbiased comparisons. This eliminates the fluctuation caused by inflation, wages and market changes. The pumps under study experienced cost fluctuations because they were manufactured over a ten year span. If all the pumps had been manufactured one year, say 1954, the correction of cost to a base year would not have been required, consequently a "cost index" established, having 1954 as the base year, covered the period of 1953 to 1962. It was arrived at by plotting the specification cost of the pumps versus year manufactured and drawing an average curve through the points. Through the use of this "cost index" all costs have been reduced to a 1954 cost basis.

All costs in this study are relative cost reduced to the base year of 1954.

Determination of the Direct Product Cost

The direct product cost is defined as the direct cost of material and labor plus the manufacturing burden at predetermined burden rates, and may be referred to as specification cost.

The direct material cost is the cost of principal items of material required to make a product. Charges for material are made to the product at the time the material is issued through the use of material requisition tickets shown in Figure 18. The direct labor cost is the cost of labor which is charged directly to the product. The document for this charge is the labor ticket shown in Figure 19. The sum of charges against the product during its passage through the factory are accumulated on the form given in Figure 20.

The manufacturing burden includes the following costs:

(a) The labor of personnel engaged in activities such as supervision, inspection, timestudy, etc.

(b) Indirect labor, such as handling of materials and supplies, electricians, janitors, trainees, standby or waiting time.

(c) Indirect materials, such as lubricants, paints, abrasives, welding and brazing wire.

(d) Maintenance and repairs.

(e) General expenses such as testing of materials and supplies, transferring of capital equipment, workmen compensation costs.

(f) Defective workmanship, material and errors.

(g) Allocated expenses such as water, light, heat and power, Social Security, insurance and vacation.

The sum of the direct material and labor costs plus the manufacturing burden give the part cost. The sum of the costs for all components gives the direct product or specification cost for a pump.

A list of the component parts of a bare pump for each group was submitted to the Accounting Department and the following is the procedure carried out to determine the product cost.

Orders for the pumps under study were selected from a complete list of customers' orders. This was compiled by the product sales department. Because of the Company's record retention policy, orders dated 1954 and after are available. The related detail material and labor ticket for orders dated 1957 and after, with the exception of government orders (1954) are also available.

Compilation of the direct product cost data required the shipping order, order specifications, and the tabulated cost report.

For flexibility in arranging and compiling costs through the use of Data Processing equipment available, a Part Cost card was prepared for each component part, including assembly costs. Data transcribed to the Part Cost card included the following:

Manufacturing date (from order specification).
Actual labor hours (make items and assembly labor).
Part number.
Order number.
Quantity.
Direct material cost.
Indirect labor cost.
Indirect manufacturing burden.

To the above data was added a group and item number to correspond with the group classification and part number.

If components within an order deviated from the standard bare pump unit, a cost for a standard component was submitted for the irregular component.

The Part Cost cards were keypunched and the unit cost calculated on a 1401 EDP data processing unit. The Part Cost cards were then mechanically sorted by part number and a listing by part number was tabulated for cost comparison purposes. The listing was reviewed for irregularities and cost fluctuations, and also for quantity irregularities such as spare parts supplied with the bare pump components for Navy pumps. The specification cost was found by summing the unit cost on Part Cost cards for each pump. The specification costs given in Table XV for each group is the average cost of all pumps in the group.

Another factor which often comes into the specification cost of a low volume product is whether it is a "stock" or a "make" item. "Stock" items are made in relatively large quantities at one time, thereby gaining the "mass production" cost advantage, whereas "make" items are manufactured only as required which increases cost because of additional machine setups, etc.

For the pumps in this study the commercial pumps are primarily "stock" items and the Navy pumps are "make" items. However, by comparing the cost of Navy pumps ordered individually against those ordered in groups of 14 at a time for Group V pumps and 8 at a time for Group VI pumps, it was found that a quantity order resulted in considerable cost decrease. However, since parts on the commercial pumps are rarely made for stock in quantities larger than thirty (30) items, even less for major parts, it was concluded that the Navy and commercial pumps costs were equally benefitted by the "mass production" factor. Consequently no quantity cost correction factor was required.

Other Manufacturing Costs

Certain manufacturing costs are often not accounted for in the direct product costs. Whether or not they are depends on the customer and the order. Generally, the costs spelled out below are accumulated for the entire Pump Section. Detailed charges against one size and type of pump, like the 5x4 SK, are not available. Instead the particular cost for all pumps sold, of all models and sizes, is known. In order to isolate these costs for each group of pumps in this study, a detailed investigation of each cost was made. The values determined as a percent of the specification cost are given in Table XV.

Engineering Expense

Engineering expense is the cost of the engineering required at the time of the order. For the Navy pumps the expense had been charged against the order and was available. Engineering expense for the commercial pumps under study was not charged against the orders. By consulting with the engineers who worked on the orders, an estimate of the cost was arrived at. The actual expenses for the Navy pumps and the average expense for all pumps served as guides. For commercial pumps a value of 5.9% of the direct product cost was found and for Navy pumps a value of 6.2%.

Research and Development

To determine the research and development cost for product improvement engineers responsible for the various pump designs were approached with this problem. Also, pump cost specialists were consulted and an estimate was obtained for all groups. The basis of the estimate was the average value expended for all pumps in 1954. An estimate of 1.8% of the direct product cost for each group was arrived at.

Engineering Changes

Engineering changes during manufacture are largely due to changes in customer's requirements.

Estimates of this cost were obtained from engineers and personnel in manufacturing. Using the 1954 average for all pumps as a guide, it was decided that a value of 0.44% of the direct product cost for all groups was realistic.

New Patterns

The costs for new patterns, flasks and chills, with their repair and storage costs, were higher for the Navy pumps than for the commercial pumps. It was estimated that for Navy pumps the cost was 1.0% of the direct product cost. For commercial pumps the expense was 2% of the direct product cost.

Small Tools Expense

From a survey of tooling requirements for the 5x4 SK pumps, it was determined that both the Navy and commercial pumps could be built using equal expenditures for tooling. Brass is used in the Navy pumps for many parts, whereas cast iron is used in the commercial pumps. Since brass is more detrimental to tooling than cast iron the tool repair costs for the Navy pumps are higher. The expenses were estimated as 0.40% and 0.50% of the direct product cost for the Navy and commercial pumps, respectively.

Adjustment of Manufacturing Burden

Adjustment of manufacturing burden is required since the burden is applied at predetermined rates on direct labor dollars. The over or under applied burden must be considered as an additional cost to the product.

It was determined by the Allis-Chalmers Works Accounting Department that for pumps this adjustment averages +5.97% of the direct product cost for pumps.

To use an average value for all pumps means that the value will be overestimated for low cost pumps and underestimated for higher priced pumps. Therefore, to determine the percentage to add to the product cost, the average manufacturing burden was determined for each group. Then the 5.97% was corrected for each group in proportion to the amount a group's manufacturing burden deviated from the average. In this manner the average percent adjustment for all groups is 5.97% but the adjustment for each group is different.

Shipping Expense

Shipping expenses involved in the preparation of a pump for transporting it to the customer is part of the manufacturer's cost. This cost occurs after the pump has been manufactured and is not included in the specification cost which is to account for the direct material, labor and burden of making the pump.

For the pumps in this study, it costs 4.25 times as much to prepare a Navy pump for shipment as it does for a commercial pump. This amounted to 3% of the specification cost for commercial and 4% for Navy pumps.

Miscellaneous Costs

Miscellaneous costs incurred are such entries as provision for inventory, material received, finished stock variance, etc. These costs are figured at 1.5% of the specification cost.

Other Costs

Selling and administrative expense are approximately the same dollar expenditure for all pumps. The cost of selling a pump to a commercial or Navy customer would be approximately equal. Therefore, this expense is not shown in Table XVI since it will not change the optimum of reliability but will only move the curve upward on the cost axis.

Transportation cost on the shipment to the customer is incurred by the manufacturer. These costs may be for rail or truck transportation of the pump. Since the pumps in this study are approximately the same weight, the cost would be a constant for any single destination. The cost of transporting the pump could affect reliability if the method used was poor and the pump was damaged in transporting it. Failures may occur as a result of damage during transportation. However, we are assuming correct techniques were used during transportation, hence, this cost is the same for all groups.

Determination of After Shipment Costs

After shipment costs to the manufacturer for the pumps were made up of warranty and good will charges. These costs are accumulated by order and pump serial by the product department. Retention of the detailed costs made them available back to 1956. These costs were tabulated for each of the eight groups. The sum of these after shipment costs are shown as a percent of the specification cost for each group in Table XV.

MANUFACTURER'S TOTAL COST VERSUS PUMP RELIABILITY PICTURE

The manufacturer's total, relative cost is shown plotted versus the actual pump reliability in Curve C, Figure 21, as the sum of the manufacturer's cost before shipment, Curve A, and the manufacturer's after shipment cost, Curve B. Curve D is the manufacturer's selling price which is arbitrarily 7% greater than the manufacturer's total cost.

The optimum level of reliability for minimum total cost occurs in a range of 250 to 275 fr/10^6 hr. for the manufacturer.

To obtain Figure 21, the failure rates had to be adjusted to a common application and operation environment to permit comparison. All are adjusted to a shipboard environment pumping sea water.

The factors which are used to correct for environmental conditions are the Application Factor (K_A) and Operating Factor (K_{OP}). Therefore, to determine the failure rate of any group in a shipboard environment the following equation is applicable.

$$\lambda \text{ shipboard} = \frac{\lambda \text{ Group i } (K_A K_{OP}) \text{ Group V}}{(K_A K_{OP}) \text{ Group i}}$$

Results are tabulated in Table XVI. On Figure 21, in addition to the adjusted group failure rates, the MTBF is also given.

As anticipated, the manufacturer's total cost before shipment does not increase very rapidly at lower levels of reliability. Increase is at a very rapid rate after a certain level is reached. Considering the pumps involved in Figure 21, mainly commercial units making up the left portion and the Navy units the right, it appears that the sudden increase began when the state-of-the-art was being advanced.

Ordinates for Group III on Figure 21 are the points in the lower righthand corner. Since the pumps in Group III are very similar to Group IV, only difference being a smaller impeller diameter, it is felt that the failure rate ordinate is in error, and that it is actually slightly less than that of the pumps in Group IV.

For comparative purposes the manufacturer's selling price must be prorated for equal pump operating periods for the pumps in all groups. A pump does not have a well defined life. Parts can be readily replaced indefinitely and the pump will not reach a worn out condition even though every part in the pump will probably have to be replaced to prevent it. Therefore, the pump's life is the period before its design or application becomes obsolete. Considering the pump applications involved in this study, a life of 30,000 hours was chosen or about 10 years of average operation. (8-hours/day). In Table XVII the initial cost per 1000 hours of operation is given and the values are also plotted in Curve A of Figure 22.

For the pumps the after shipment costs are negligible in comparison to the before shipment costs. Since these pumps have such a comprehensive design background, it can be realized that early failures due to faulty design and manufacture are not likely to occur, and warranty costs would be low.

The largest factor in the pumps' before shipment cost is the direct product cost. For the commercial pump groups, Groups I, II, III, IV, VII, and VIII, this cost is made up in the following manner:

Direct Materials	35-45 %
Direct Labor	15-20%
Manufacturing Burden (Facilities)	35-45%

For the Navy pump groups, Groups V and VI, the breakdown shows the following pattern:

Direct Materials	50-55%
Direct Labor	12-15%
Manufacturing Burden (Facilities)	30-35%

CUSTOMER'S COSTS

Costs obtained for the customer as outlined in "Customer Reliability versus Total Product Cost Picture" and in "Data Sources Acquisition" are presented here.

The customer's purchase price for the pump is arrived at by adding to the manufacturer's total cost, shown in Table XV, an arbitrary fee of 7%. The customer's purchase price is tabulated for each group in Table XV.

The next cost to be considered is the repair and replacement expense of unscheduled outages or failures. All failures had been identified in advance of the failure rate calculation. Parts replaced during an unscheduled outage, as shown by the Machinery History Card, Centrifugal Pump Reliability Report or Fluid Dynamics Renewal Parts Section Records, were listed for each group. The total number of each part used during unscheduled repairs was found. The cost of each of these parts based on 1954 prices was obtained from the Fluid Dynamics Renewal Parts Section. The total part cost was obtained by summing the product of the part cost and the number of parts used for all parts. The cost of gaskets, bolts and nuts was considered negligible. Replacement of drain valves and the associated piping on the Navy pumps was not considered since they are not part of the pump being studied.

When repairs were made, these costs were estimated by using the detailed part costs as determined by the Accounting Department. For example, if a shaft was built up and remachined, the cost was estimated as equal to the initial manufacturing machining cost. Cost of replacement and repair of parts due to failures is tabulated on Table XVIII, designated as "Unscheduled Replaced Parts".

Labor cost for the removal and replacement of parts was determined through the use of a teardown and assembly chart. This chart was constructed using Timestudy data obtained for pumps very similar to those under study. In addition time was spent in the pump assembly area observing the assembly of 5x4 SK pumps. Personnel in the Service Section of Fluid Dynamics reviewed the teardown and assembly chart and found it consistent with service experience. Using the chart the man hours required to complete all of the unscheduled repairs as indicated by the data forms were computed. By multiplying these by an hourly rate, the "Unscheduled Labor" costs on Table XVIII were found. The labor rate used in this study is $5.32 per hour. This value is the average wage paid to Allis-Chalmers production employees in 1954 with a 120% burden added. The burden rate was determined as the average burden of several machinists, pipefitters and other maintenance groups within Allis-Chalmers.

By multiplying the unscheduled labor hours by the downtime rate of $100 per hour the "Unscheduled Downtime Cost" was found. This is also tabulated in Table XVIII for all groups. Calculation of the downtime cost in this manner assumes that one man repairs the pump. Then the repair time and downtime due to repair are the same. This approximation is satisfactory for the size of pump under study.

The "Scheduled Replaced Parts" and "Scheduled Labor" costs were determined in the same manner as the "Unscheduled Replaced" and "Unscheduled Labor" costs respectively.

The customer's cost must be compared based on pump operation in the same environment. As was with the failure rates, all the customer's costs are determined as if all the groups were operating on shipboard pumping sea water. Costs to the customer have to be compared based on a finite period of time, i.e., per hour or per year. In this study the time period was taken as 1000 hours. Table XVII shows the purchase price of a pump in each group prorated over 30,000 hours.

The customer's unscheduled costs, labor, parts and downtime can be adjusted to common base in the same manner that the failure rates were, since these costs are a function of the failure rate only.

It is assumed in this study that all the customers have followed the customer's preventive maintenance recommendations for these pumps. And in the case of all the pumps under study the recommendations are the same, therefore T, the period between scheduled repairs can be assumed equal for all the pumps operating in the same environment. These pumps do not vary drastically in the number of parts used, and the parts which wear out frequently are the same. Cost of the parts replaced vary approximately in the same proportion as the purchase price of the pumps.

Consequently, based upon the above reasoning, in the calculation of the preventive maintenance labor cost the same value, that of Group V, was used for all groups for comparative purposes. Cost of preventive maintenance parts was adjusted to the shipboard, sea water environment by taking the cost of preventive maintenance or scheduled replaced parts for Group V and multiplying it by the ratio of each group's purchase price to that of the pumps in Group V.

Other costs for the customer, such as installation, floor space and operating costs (cost of power) do not affect, and are not affected by, reliability. Therefore, they do not have any effect on the optimum reliability-minimum cost picture.

CUSTOMER'S TOTAL COST vs. PUMP RELIABILITY PICTURE

The customer's total costs for all groups are tabulated in Table XIX for the pumps, operating in a shipboard sea water environment, per 1000 hours of operation, and are plotted versus failure rate and MTBF. See Figure 22.

The total cost picture shows that the optimum reliability is in the range of 125-145 fr/10^6 hours.

In Figure 22, the pumps' purchase price per 1000 hours of operation increases with reliability and is only a fraction of the customer's total cost. The predominating cost is the unscheduled repair cost. Major contributing component in it is the unscheduled downtime cost. As seen in Table XIX the unscheduled and scheduled repair costs are approximately the same in most cases.

If the unscheduled downtime cost is not considered, as it may not be for Navy applications, then the optimum level shifts to the left to a failure rate of 165-175 fr/10^6 hours. This can be seen in Figure 23.

Of the three major cost components shown in Figure 22, the initial purchase price is the lowest. This curve is based on pump lives of 30,000 hours. If the life chosen is too long, the optimum point will slightly shift to the left. Pump designs with higher failure rates and lower initial cost will then be optimum. It is more likely though that the lives of these pumps were chosen too short, since aboard one aircraft carrier they have already accumulated 15,000 hours in approximately eight years. Also some commercial units have accumulated more than the 30,000 hours in less than ten years of operation. Pump life could be defined in other ways, such as when the casing or impeller is worn out, or the time to first failure. It is felt that using a life of 30,000 hours would most closely fit the life of these pumps from the customer's point of view.

The scheduled repair costs are higher than the prorated initial cost of the pump. For Group V, Navy pumps, the dollars spent are nearly twice that of the prorated initial cost per 1,000 hours of operation. For both groups of Navy pumps, Groups V and VI, the cost of scheduled repairs is several times the cost of unscheduled repairs, without including downtime cost. This could be the result of the following two factors: (1) Unscheduled downtime of these pumps is not tolerable and perhaps the $100 per hour downtime cost used in this study is a good estimate for the Navy. (2) The pumps are over-maintained to provide experience for maintenance crews.

In other words, unscheduled downtime cost is one of the major factors which make frequent scheduled repairs of the pumps necessary.

Until the Navy and commercial customers place values, in terms of dollars, manhours, or relative to other equipment, on the unscheduled downtime of equipment, it will be difficult for manufacturers to produce equipment with optimum reliability. Also, the manufacturer will be stymied in attempting to provide engineering help on problems in redundant equipment, spare provisioning, maintenance requirements and manning needs.

It is fully realized that the seriousness of equipment downtime varies with the operational mode of the equipment and the ship. This is a multivariable problem which can be handled with probability and engineering analysis.

The major cost on Figure 22 is the unscheduled repair cost. The primary component in this cost is the unscheduled downtime cost. If this value is zero then the customer's cost picture is changed. (See Figure 23). With this change the optimum level of reliability shifts to the left. The optimum value from Figure 23 is in the range of 165 to 175 fr/10^6 hr. Unless a pump is doing a menial task, it is unlikely that the unscheduled downtime cost will be negligible. The following four considerations suggest possible incurred costs:

(1) If standby equipment is kept in readiness, then the cost of the standby equipment is chargeable as unscheduled downtime cost.

(2) If other equipment is kept from operating a loss is involved.

(3) If manpower is put on waiting productivity is lost.

(4) If a service being performed by the equip-stops, again productivity is lost.

The degree of importance in each case obviously may be different and varies depending upon the equipment.

CONCLUSIONS

The results of this study permit the following conclusions:

(1). Figure 22 shows that there is an optimum reliability level at which the total cost of these pumps to the customer and the manufacturer is minimum. This level is a function of the pump price, parts cost, random and wearout failure rates, part and pump life, environment, and maintenance practices.

(2) For the customer the optimum pump failure rate is in the range of 125-145 fr/10^6, with a mean of 135 fr/10^6 hr. For the manufacturer it is in the range of 250-275 fr/10^6 hr. with at about 263 fr/10^6 hr.

(3). ..e optimum pump failure rate of 135 fr/10^6 hr. is very close to the failure rate for Navy pumps of 115 fr/10^6 hr. (Group V).

(4). Figure 22 shows that the support costs for these pumps is several times the purchase price. Even if the pumps are not penalized for unscheduled downtime costs, the support cost would still be several times the initial cost. However, for land installation for use with clear water, the support cost would be only a small fraction of the initial cost as may be seen in Table XVIII. This points out the great significance of the pump application and operating environment on its reliability and cost, as a result of which the optimum level of reliability will change. The manufacturer should therefore obtain an exact description of the environment in which the pump is going to operate before recommending the optimum pump for that application.

(5). It became apparent during this study that neither the customer nor the manufacturer kept adequate, easily retrievable records of either costs or pump performance data. Efforts are being made in this area, but most are in their infancy. The Navy's Machinery History Card, when properly filled in, produces very useful data, but often the very important hours of operation are not given. The Navy's failure reporting program is of an exceptional nature in concept but has not been successful in getting the failures reported. The commercial customers often do not keep detailed enough records of how, when and why of problems.

(6). The manufacturer and customer should not only optimize reliability with respect to reliability, but also consider the optimum preventive maintenance practice. This is a multi-variable problem on which more work needs to be done.

(7). The random failure rate of the pumps studied is negligible, and the failure rates are governed more by the mean wear-out life of the components (17). Therefore, in order to increase the reliability of any of the pumps the individual part mean lives must be increased. It is important to note that although the failure rate of Group V is approximately constant, the failure rates of the individual parts are not.

(8). Figure 21 corresponds to the righthand portion of the cost curves given in Figure 1. The pumps are all designed at low enough stress levels and, furthermore, the manufacturing processes involved are well enough developed that extremely few early failures or random failures occur.

(9). Figure 22 corresponds more to the lefthand portion of the cost curves presented in Figure 2. Here the support cost is much greater than the initial price and the optimum reliability for the customer is considerably to the right of that for the manufacturer. The manufacturer, for his own benefit in maintaining good customer relations, should design the pump at the customer's optimum to minimize the customer's support costs. As it may be seen by the proximity of the Group V, Navy pump failure rate to that of the optimum in Figure 22, Allis-Chalmers already has accomplished this.

(10). The cost of scheduled and unscheduled repairs for each group is approximately twice the pump purchase price on a cost per 1000 hours of operation basis. The unscheduled repair and scheduled labor costs can be reduced by using parts with longer lives, however these parts will definitely cost more; and therefore the purchase price and scheduled repair parts cost will increase.

(11). Figure 22 indicates that a total cost savings of 45% can be made by spending only about 40% more at the time of the purchase. This is arrived at by comparing the total cost and purchase price values of Group I pump with those of the optimum pump at R_{OC}.

RECOMMENDATIONS TO THE MANUFACTURER

The efforts, procedures, data acquisition techniques, the quality of data obtained, methods of analysis of this data, and the results of this study bring forth the following recommendations to the manufacturer:

(1) A concerted effort needs to be expended in improving the following documents:

(a) A number of Product Reliability Forms should be developed for each major product line. These forms should be complete and when properly filled out, should provide information from which early life, useful life and wearout failure rates can be calculated, and customer's support costs can be obtained.

(b) The accounting forms should enable the accumulation of the specific cost items that make up the manufacturer's before and after shipment costs on the basis of a specific product in a department rather than on a product department basis where more than one and varied products are involved.

(2) All necessary steps should be taken to motivate all disciplines involved to objectively compile the required reliability and cost data.

(3) The failure rates and all costs should be calculated at frequent enough intervals to enable their monitoring and the establishment of the optimum level of failure rate for minimum total cost.

(4) An increasing effort should be expended to attain and maintain the optimum level of reliability for a specific product.

(5) An integrated reliability program should be implemented, to make everyone that deals with a product from birth to death conscious of the existence of an optimum reliability goal for each product and to educate them in the science of reliability so that they can design and build the optimum target reliability into the product.

(6) Preventive and repair maintenance schedules should be scientifically worked out by the manufacturer based on

the product's reliability bath-tub curve so that these maintenance costs, which most frequently are far greater than the purchase price of the product, are minimized over its life.

(7) A product's operation and maintenance manual should be prepared with the optimum reliability in mind. The maintenance schedule should include the groups of components that should be replaced at each scheduled maintenance.

(8) When bidding on a request for a proposal, an extraordinary effort should be expended to quote on the customer's total cost, as well as on the initial cost basis. The manufacturer should emphasize in his proposal that he has expended the effort of developing the customer's total product cost, and that the customer should base his selection of the successful bidder on this total cost basis.

(9) Enough significant failure rate data should be obtained to determine for which components development and component selection money should be expended. These components would have relatively high failure rates or be responsible for a major portion of the support costs.

(10) Figure 22 shows that the manufacturer is supplying a pump to the Navy that has a failure rate (115 fr/10^6 hr.) very close to the Navy's optimum or 135 fr/10^6 hr.

(11) The manufacturer should provide design improvements that would minimize misalignment among the rotating and stationary pump assemblies and the drive motor. Customer data show that a large proportion of early failures are due to such misalignment.

(12) Special tools should be developed for the user so that pump bearings can be assembled by Navy maintenance personnel with minimum of cocking in their seat. Furthermore, an identification should be provided so that these bearings would not be inserted wrong face in into their respective bores. Many bearing failures, and most of them after only 300 to 400 hours of operation, are due to improper assembly practices.

(13) The manufacturer should use, and to great advantage, the pump field failure rate prediction technique developed in this study for new pump designs to be introduced in the future.

Through this technique, the engineering of a product may be done in advance of hardware availability, thus permitting an early trade off analysis to optimize component design and selection.

(14) The Navy pump bath-tub curve of Figure 16 should be used to determine the spare part requirements and provisioning schedules, as the area under the curve is equal to the failures for which spare parts are required. Using techniques of pump failure rate apportionment to components, coupled with a consequential failure analysis, the spares required for each pump may be determined.

(15) Figure 16 indicates erratic preventive maintenance practices. This may be minimized by preparing a comprehensive life long preventive maintenance manual for the Navy. A close study of the Machinery History Cards should reveal the best preventive maintenance practice for each pump type on an optimized basis. Reference (17) should be used to accomplish this. This should reduce spare part requirements, the number of preventive maintenance actions and maintenance crews.

(16) The bath-tub curve for Group V indicates a high early failure rate. Since these failures have not been reported as the result of faulty workmanship or material on the part of the manufacturer, they must have been the result of incorrect installation, maintenance or an abnormal environment such as pumping sand through the pump. Because of this, the manufacturer should maintain close liaison with the customer to isolate and solve this problem.

RECOMMENDATIONS TO THE CUSTOMER

(1) The customer should in the near future, require that costs in all proposals be submitted on the customer's total cost basis.

(2) The customer should request that all proposals contain total cost versus useful life reliability versus total maintenance cost curves based on several preventive maintenance schedules, for total cost optimization.

(3) The customer should learn how to incorporate the optimum reliability level into its technical specifications, how to seek it and how to monitor it.

(4) The customer should vigorously pursue a practice of fully documenting all of the pertinent reliability, cost and maintenance data during the life of a product and of making available this data to the manufacturer for his analysis and action.

(5) The customer should incorporate in his procurement document clauses for rewarding the manufacturer upon attainment of the optimum reliability goals and for penalizing him on default.

(6) The bath-tub curve of Figure 16 and a study of the entries on the Machinery History Cards indicates that much erratic maintenance is being performed on the Navy pumps. It is urged that the manufacturer's maintenance recommendations be dutifully followed, as much as is feasible, to minimize the maintenance cost and reduce maintenance crew requirements.

(7) The maintenance crew should be better trained because the excessive frequency of maintenance performed indicates that misalignments and wrong component assembly practices during maintenance abound. Shaft breakages, too numerous bearing replacements, undue shaft sleeve replacements due to wearout can be minimized by better trained maintenance crews.

(8) Figure 22 shows that the Navy is being supplied by the manufacturer a pump very close to the optimum. It is recommended that the Navy continue procuring such pumps having a failure rate within the range of 125 and 145 fr/10^6 hr.

(9) The Navy's Machinery History Cards are well conceived, however they are not being completely filled out. The most important bit of information, namely, hours in the life of the pump when a particular maintenance is performed, is very frequently missing. The date the pump was put into operation should be entered, as well as the exact observation that led the crew to decide to perform the particular maintenance.

(10) A concerted effort should be expended to get back a greater proportion of the failures reported on the BuShips Failure Reports. Presently, only between 10 and 20% reporting is being achieved. These reports should be matched with entrees on the Machinery History Cards for completeness and for cross-check on the efficiency of the failure reporting system used.

(11) The Navy, as well as other customers, should use preventive and repair maintenance records to formulate optimum corrective action practices and feed back this information to the manufacturer for his perusal and preparation of operation and maintenance manuals.

(12) The customer should motivate his personnel dealing with the product into observing all reliability practices recommended by the manufacturer and into using all specified reliability documentation media faithfully.

(13) The customer should promote the development of bathtub curves and should use same, so that he optimizes his spare part procurement and storage requirements.

(14) As the customer's support costs for these pumps are several times the purchase price, the customer should exercise stricter control over the application environment of these pumps because a slight increase in the severity of this environment, such as sucking sand into the pumps while at port, increases the maintenance or support cost sharply.

RECOMMENDATIONS ON THE IMPROVEMENT OF THE QUALITY OF RELIABILITY AND COST DATA

Special efforts should be made to improve the quality of reliability and cost data. These should include the following:

(1). Motivate every engineering, manufacturing, and cost center to compile complete reliability and cost data. The details of such data and specific problems were discussed in the respective cost sections.

(2). All pertinent forms for the acquisition and processing of this data should be redeveloped and well integrated.

(3). The use of such forms has to be put on an almost compulsory basis.

(4) Special questions should be provided for certain classes of customers, such as the different segments of commercial and military customers.

(5). The information sought should be recorded on specific forms developed for specific information, i.e., failure data on one form, spare parts on another, scheduled maintenance cost on another, etc. This would facilitate the collection of the required information.

(6). The explanation of an entry on the form should be directly beneath the question asked. This explanation will vary, depending on the class of customer being questioned.

(7). The customer should be made aware of how the information being requested is to be used. He should be given an opportunity to answer a question in his own way if this is permissible. As an example, the customer may want to state the cost in dollars or hours.

(8). The operating environment should be more clearly explained by the customer. To get this information from him, the form will have to be more specific and apply directly to the industry in question.

(9). The customer should be encouraged to send copies of his records along with the completed form. If the customer is assured that the records will be confidential, he may be willing to cooperate. These records will contain information overlooked by the customer as being applicable to reliability.

(10) A checklist type of reply appears to be the most productive. In this study the most useful information was obtained where checkoff blocks were used.

(11). Tolerances or ranges should be requested on specific data sought to give the customer the opportunity to check off the range most applicable to his case.

(12). It would be productive to send the customer film strips, slides, posters, or literature prior to his filling out the form. These modes of communication would set the stage for better and more useful information.

(13). The customer should be encouraged to write comments.

(14). The questions should be numbered for electric machine card key punching and processing.

(15). Repeat questions should be provided worded to differently provide a check on the previous information entered.

It whould be realized that it is a never ending challenge to both the manufacturer and the customer to obtain, compile, properly document, and analyze reliability and cost data. The importance of this challenge should never be minimized. After all. progress is brought by analysis of facts which can best be presented in data form.

RECOMMENDATIONS FOR FUTURE STUDIES

(1) Funds should be made available to conduct a similar study on other **DOD** products to determine how the optimum useful life and wearout life reliabilities shift.

(2) Studies on cost optimization for the totality of useful life reliability, wearout life reliability, total inventory cost, (cost of product procurement and of possession) maintainability, availability and safety should be undertaken.

(3) Studies to develop multivariable optimization techniques should be undertaken.

(4) Funds should be made available to develop further the methodology of predicting mechanical system reliabilities.

(5) Studies should be conducted to develop techniques for designing a specified failure rate directly into a product and its components.

(6) More studies should be conducted to develop bath-tub curves for mechanical subsystems and systems to see whether the prevailing useful life reliability emphasis has basis for the majority of such mechanical subsystems and systems.

(7) Studies should be conducted to develop reliability checklists for engineering, manufacturing, quality control, sales, service, maintainability, and customer data feedback to help attain and maintain the optimum reliability level.

(8) Optimum spare part provisioning techniques should be developed based on reliability bath-tub curves.

(9) Component and equipment design techniques should be developed whereby the "One-Horse Shay" concept is approached, if not attained, thus minimizing very costly preventive maintenance.

(10) Studies to develop more effective and efficient failure reporting, data feedback, and corrective action procedures should be undertaken. The field failure and performance data should be properly identified and

classified, failure rates calculated at regular intervals, coded and stored for easy retrieval. The time required to complete studies, such as this, may be drastically reduced in this manner.

(11) Studies should be conducted to determine the effect of startup and shutdown on equipment reliability. This would help in the optimization of the total maintenance costs and in the design of components.

(12) More studies should be conducted to determine the effects of various application and operating environments on component and system failure rates, to increase the accuracy of reliability predictions.

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LIST OF TABLES

LIST OF FIGURES *

*The figures follow the tables.

LIST OF FIGURES, cont.

TABLE I

PUMP DESIGN AND MATERIAL CHANGES

Component	No. of Changes	Type of Change
Impeller	2	Width - 15/16" and 3/4"
Impeller	Numerous	Dia. - 7" to 11" in approx. 1/8" increments
Shaft	2	Dia. - 1.467" and 1.687"
Shaft	3	Material - SAE 1045 Hot Rolled Steel Ni-Cu (Monel) Stainless Steel
Shaft Sleeve	2	Dia. - 1.468" I.D. and 1.687" I.D.
Shaft Sleeve	3	Length - Standard 5/8" shorter 3/4" longer
Shaft Sleeve	5	Material - Bronze AB Monel Stainless Steel ACM 141 (Allis-Chalmers Designation) SAE 1045 - Hot Rolled Steel
Bearings	4	Oil Lubricated Sleeve - "SB" Oil Lubricated Single Row Ball "B1O" Grease Lubricated Single Row Ball "B1G" Grease Lubricated Double Row Ball "B2G2"
Bearings	1	Snap Ring Added
Casing Ring	5	Standard Larger Bore and 1/8" Thinner Larger Bore and 1/16" Thinner Larger Bore and 1/8" Thicker Adjustable

TABLE I (Continued)

Component	No. of Changes	Type of Change
Casing Ring	4	Materials - Stainless Steel Bronze E Cast Iron 25 ACM 144
Casing	4	Materials - Cast Iron 25 Stainless Steel Gun Metal Bronze EH
Packing and Seal	3	Materials - Soft Asbestos Fleximetal Mechanical Seal
Seal Cage	2	Standard - C.I. Gun Metal
Other Components	8	Angle Valve Instead of Aircock Tee Handle Oil Rings Alemite Collar Snap Ring for Bearing Bearing Adapter Adapter Cap Dowel Bearing Deflector

TABLE II

APPLICATION ENVIRONMENTS OF 5x4 TYPE SK AND KSK PUMPS

I. Type of Fluid Pumped

A. Description

1. Pure water
2. Water with significant impurities
3. Sea water
4. Brine (higher salt concentration than sea water)
5. Industrial chemicals
6. Petroleum products
7. Water with significant solids

B. Temperature ranges from ambient to 190°F.

C. Specific gravity from 0.9 to 1.9

D. Viscosity ranging from that of water to over 300 SSU.

II. Hydraulic operation from near shutoff to 35% in excess of rated flow.

III. Discharge pressures 0 to 250 psi.

TABLE III

OPERATING ENVIRONMENTS FOR 5x4 SK AND KSK PUMPS

Group	Ground Environment
1. a.	Condensate, Feedwater and Booster Pumps.
b.	Fire Pumps.
2.	General Service Pumps in Utility Companies.
3. a.	General Service Pumps in Other Industries Such as Cement, Glass, etc.
b.	General Service Pumps in Paper Industry.
4. a.	Irrigation Pumps.
b.	Stream Barker Service Pumps.
5. a.	Hydraulic Mining Service.
b.	Oil Company Service.

	Shipboard Environment
1.	Fuel Pumps (Navy).
2. a.	Fire Pumps (Navy).
b.	Tanker Fire and Butterworth Service Pumps.
3.	Catapult Water Brake Pumps (Navy).

TABLE IV

FINAL GROUPINGS

FROM PRELIMINARY GROUPINGS*

Final Group No.	Preliminary No.
I	1, 2, 3
II	1, 2, 3
III	4, 5, 6
IV	4, 5, 6
V	11
VI	12
VII	15, 16, 17
VIII	15, 16, 17

*Preliminary Groupings 7, 8, 9, 10, 13, 14 and 18 have been deleted. See text for reasons.

Table Va

FINAL PUMP RELIABILITY GROUPINGS AND THEIR COMPARATIVE DIFFERENCES

(Groups I through V)

Group	No. of Pumps	Shaft	Shaft Sleeve	Casing Ring	Ball Bearing
I	15	Small dia. shaft D = 1.468"	Small dia. 6-3/8" long	Bronze 'E'	B1G
II	17	Small dia. shaft D = 1.468"	Small dia. 6-3/8" long	Bronze 'E'	B1G
III	10	Larger dia. shaft D = 1.687" instead of 1.468"	Larger dia., longer by 3/4". Some pumps have ACM 141 shaft sleeve instead of bronze 'AB'	Bronze 'E'	B1G
IV	13	Larger dia. shaft D = 1.687" instead of 1.468"	Larger dia., longer by 3/4". Some pumps have ACM 141 shaft sleeve instead of bronze 'AB'	Bronze 'E'	B1G
V	90	Larger dia. tapered shaft of Ni-Cu alloy D = 1.687" instead of 1.468"	Larger dia., longer by 3/4". Shaft sleeve of Ni-Cu alloy.	Bearing bronze casing ring with larger bore but 1/16" thinner	B2G2

Table Va (Continued)

Group	Impeller	Casing	Others	Application
I	Larger dia. impeller. Wide outlet 7.0" to 9.0" dia. Narrow outlet 7.0" to 9.50" dia.	CI 25		Commercial
II	Larger dia. impeller. Wide outlet 9.0" to 11.0" dia. Narrow outlet 9.50" to 11.0" dia.	Some pumps in this group have BR 'EH' casing instead of C.I. 25	Some of the pumps in this group have outside seals	Commercial
III	Larger dia. impeller. Wide outlet 9.0" to 11.0" dia. Narrow outlet 9.5" to 11.0" dia.	CI 25		Commercial
IV	Larger dia. impeller. Wide outlet 9.0" to 11.0" dia. Narrow outlet 9.5" to 11.0" dia.	CI 25		Commercial
V	Larger dia. impeller of Ni-Cu alloy instead of bronze with wide outlet. Diameter = 10-1/8"	Gun metal casing instead of C.I. 25	Shaft nuts, ball bearing adapters, adapter caps, bearing caps, glands are of gun-metal instead of BR 'AB'	Navy pump used as fire pump

Table Vb

FINAL PUMP RELIABILITY GROUPINGS AND THEIR COMPARATIVE DIFFERENCES

(Groups VI through VIII)

Group	No. of Pumps	Shaft	Shaft Sleeve	Casing Ring	Ball Bearing
VI	16	Larger dia. tapered shaft of steel, D = 1.687" instead of 1.468"	Larger dia., longer by 3/4" shaft sleeve of Ni-Cu alloy	Bearing bronze casing ring with larger bore but 1/16" thinner	'B2G2 bearings
VII	20	Larger dia. shaft of carbon steel. D = 1.687" instead of 1.468"	Larger dia. sleeve with taper at key-way end and short by 5/8"	Larger bore and thicker by 1/8". It has 1/8" groove instead of tongue	Snap ring bearing retainer is used, B1G
VIII	14	Larger dia. shaft of carbon steel. D = 1.687" instead of 1.468"	Larger dia. sleeve with taper at the keyway end and short by 5/8"	Larger bore and thicker by 1/8". It has 1/8" groove instead of tongue	Snap ring bearing retainer is used, B1G

Table Vb Continued

Group	Impeller	Casing	Others	Application
VI	Wide outlet impeller of Ni-Cu alloy instead of bronze. Diameter 7" to 8.30"	Gun metal casing instead of C.I. 25	Shaft nuts, ball bearing adapter caps, bearing caps, glands are of gun metal instead of BR 'AB'	Navy pump, used as catapult fresh water brake pump
VII	Larger dia. impeller. Wide outlet 7" to 9.0", narrow outlet 7" to 9.5" dia.	CI 25	Spacer sleeve, ball bearing adapter, adapter cap, alemite collar, valve stem and straight dowel are not used, but bearing housing, bearing cover and deflector are used	Commercial
VIII	Larger dia. impeller. Wide outlet 9.0" to 11.0". Narrow outlet 9.5" to 11.0" dia.	CI 25	Spacer sleeve, ball bearing adapter, adapter cap, alemite collar, valve stem and straight dowel are not used, but bearing housing, bearing cover and deflector are used	Commercial

TABLE VI

GENERIC FAILURE RATES FOR 5x4 SK AND KSK PUMP COMPONENTS

Table VI-a: Failure rates of components common to all groups

Component Name	Generic Failure Rate fr/10^6 hr. Max.	Mean	Min.
Shaft	0.62	0.35	0.15
Shaft Sleeves (2)*	0.60	0.30	0.04
Casing Bushing (2)	0.16	0.10	0.04
Shaft Nut (2)	0.0152	0.0084	0.0048
Casing Ring (2)	0.16	0.10	0.04
Straight Key	0.28	0.14	0.08
Step Key	0.18	0.09	0.05
Grease	0.016	0.010	0.004
Permatex	0.000	0.000	0.000
"O" ring (2)	0.06	0.04	0.02
Impeller	0.24	0.15	0.06
Casing	0.910	0.400	0.016
Gland (4 halves)	0.20	0.125	0.05
Gland Bolts-½" (4)	0 061	0.034	0.019
Seal Cage (4 halves)	0.08	0.05	0.02
Gasket (3)	0.675	0.414	0.150
Packing (2)	1.12	0.70	0.25
Cap Screw (12)	0.0455	0.0250	0.0145
Lock Washer (12)	0.0455	0.0250	0.0145
Pipe Plug (2)	0.000	0.000	0.000
Hex. Set Screw (2)	0.0152	0.0084	0.0048
Crank Case Sealer	0.016	0.010	0.004
Taper Dowel (2)	0.015	0.008	0.005
Bearing Cap (2)	0.6066	0.2666	0.0106
TOTAL	6.1210	3.3544	1.0472

*The number in parentheses indicates the number required. The failure rates given in the three columns are multiplied by the number.

Table VI-b: Generic failure rates of additional components required for pumps in groups I, II, III, IV.

Component Name	Generic Failure Rate fr/10^6 hr Max.	Mean	Min.
Ball Bearing Adapter (2)	0.242	0.174	0.007
Adapter Cap (2)	0.082	0.025	0.001
Spacer Sleeve (2)	0.16	0.10	0.04
Bearing End Plate (2)	0.280	0.176	0.070
Ball Bearing #6206 or 6207	3.080	1.570	0.062
Ball Bearing #6305 or 6306	2.620	1.340	0.053
Oil Hole Cover (2)	0.000	0.000	0.000
Alemite Collar (2)	0.000	0.000	0.000
Valve Stem (2)	0.540	0.336	0.104
Straight Dowel (2)	0.015	0.008	0.005
Aircock Tee Handle	0.140	0.084	0.026
S.F. Hex. Nut (4)	0.030	0.016	0.010
Drive Screw (2)	0.000	0.000	0.000
Lock Washer (2)	0.0080	0.0040	0.0025
Lock Nut (2)	0.0080	0.0040	0.0025
Alemite Fitting (2)	0.089	0.055	0.022
Taper Dowel (4)	0.03	0.016	0.010
Cap Screw (21)	0.1575	0.0840	0.0525
TOTAL	7.485	3.9920	0.4675
Total Generic Failure Rates of Common Components (Table VI-a)	6.1210	3.3544	1.0472
Total for Groups I, II, III, and IV	13.6060	7.3464	1.5147

Table VI-c: Generic failure rates of additional components required for pumps in groups V and VI

Component Name	Generic Failure Rate fr/10^6 hr Max.	Mean	Min.
Ball Bearing Adapter (12)	0.242	0.174	0.007
Adapter Cap (2)	0.082	0.025	0.001
Bearing End Plate (2)	0.280	0.176	0.070
Ball Bearing C.E.	2.8500	1.4500	0.0575
Ball Bearing O.E.	2.1700	1.1125	0.0440
Oil Hole Cover (2)	0.000	0.000	0.000
Alemite Collar (2)	0.000	0.000	0.000
Valve Stem (2)	0.540	0.336	0.104
Straight Dowel (2)	0.015	0.008	0.005
Aircock Tee Handle	0.140	0.084	0.026
S.F. Hex.Nut (4)	0.0132	0.003	0.0042
Drive Screw (2)	0.000	0.000	0.000
Lock Washer (2)	0.0080	0.0040	0.0025
Lock Nut (2)	0.0080	0.0040	0.0025
Straight Hydraulic Fitting (2)	0.089	0.055	0.022
Taper Dowel (4)	0.03	0.016	0.01
Stud (21)	0.0798	0.0441	0.0252
S.F. Hex.Nut (21)	0.0798	0.0441	0.0252
Angle Valve (2)	0.000	0.000	0.000
Coupling Lock Nut	0.0076	0.0042	0.0024
TOTAL	6.6344	3.5399	0.4082
Total Generic Failure Rates of Common Components (Table VI-a)	6.1210	3.3544	1.0472
TOTAL for Groups V and VI	12.7554	6.8943	1.4554

Table VI-d: Generic Failure Rates of additional components required for pumps in group VII and VIII

Component Name	Generic Failure Rate fr/10^6 hr Max.	Mean	Min.
Bearing Housing (2)	0.6066	0.2666	0.0106
Bearing Cover (2)	0.16	0.10	0.04
Deflector (2)	0.16	0.10	0.04
Ball Bearing #6207	3.080	1 570	0.062
Ball Bearing #6306	2.620	1.340	0.053
Snap Ring (2)	0.18	0.09	0.05
Drive Screw (2)	0.000	0.000	0.000
"O" Ring (4)	0.12	0.08	0.04
Cap Screw (21)	0.1575	0.0840	0.0525
TOTAL	7.0841	3.6306	0.3481
Total Generic Failure Rates of Common Components (Table VI-a)	6.1210	3.3544	1.0472
TOTAL FOR GROUPS VII and VIII	13.2051	1.9850	1.3953

TABLE VII

APPLICATION FACTORS FOR 5x4 SK and KSK PUMPS

			K_A
1.	Pure water	0-4% impurities	1.0
		5-9% "	1.1
		10-14% "	1.2
2.	Pure water with significant impurities	15-20% "	1.3
3.	Salt water non-corrosive material		2.75
4.	Salt water corrosive material		4.0
5.	Salt water non-corrosive material with impurities		3.5
6.	Brine, corrosive material		5.0
7.	Brine, non-corrosive material		3.5
8.	Operation at 0-15% variation from rated		1.0
9.	Operation at 16-35% variation from rated		1.1
10.	Operation at 36-100% variation from rated		1.2
11.	Operation near shutoff	Never	1.0
		Occasionally	1.1
		Frequently	1.2
12.	Temperature (a) Packing	0-91°F	1.0
		91-190°F	1.2
		over 190°F	1.4
	(b) Bearings	0-90°F	1.0
		91-190°F	1.15
		over 190°F	1.25

(c) The fluid temperature encountered in the use and application of these pumps would have a negligible effect on the failure rate of the other components.

TABLE VII (Continued)

13.	Specific gravity	Up to .9	.9
		.9 to 1.1	1.0
		over 1.1	1.1
14.	Viscosity	Under 150 SSU	1.0
		150-300 SSU	1.10
		over 300 SSU	1.15
15.	Discharge pressure	0 to and including 150 PSI	1.0
		150 - 250 PSI	1.2

TABLE VIII

AVERAGE GROUP K_A & K_{OP} FACTORS FOR 5X4 SK AND KSK PUMPS

GROUP NO.	K_A	K_{OP}
I	1.23	6.20
II	1.17	7.00
III	1.11	5.9
IV	1.12	6.42
V	4.375	14.00
VI	1.28	16.00
VII	1.13	7.00
VIII	1.52	6.85

TABLE IX

5x4 SK & KSK PUMP OPERATING ENVIRONMENTS AND KOP FACTORS IN INCREASING ORDER OF SEVERITY

Classification	Ground Environment	K_{op}
1.a	Condensate, Feedwater and Booster pumps	4.5
b	Fire pumps	
2.	General Service pumps in utility companies	5.5
3.a	General service pumps in other industry such as cement, glass, etc.	7.0
b	General service pumps in paper industry	
4.a	Irrigation pumps	8.0
b	Stream barker service pumps	
5.a	Hydraulic mining service	9.5
b	Oil company service	
	Shipboard Environment	
1	Fuel pumps (Navy)	12.0
2.a	Fire pumps (Navy)	14.0
b	Tanker fire and Butterworth service pumps	
3	Catapult water brake pumps (Navy)	16.0

TABLE X

PUMP GROUPS CLASSIFICATION INTO DESIGN CLASSES

AND

THE DESIGN GROUP FACTOR, K_G

Design Class, i	Group No.	E_i-Ratio of λ of a Class to λ of Class 0	K_G
0	VI	1.00	0.633
1	V	1.29	0.816
2	III	1.58	1.000
3	I, IV, VII	1.87	1.183
4	VIII	2.16	1.369
5	II	2.45	1.55

TABLE XI

PART FAILURE RATE RATIOS FOR SK AND KSK PUMPS

Name of Component	Max. Generic Failure Rate / Min. Generic Failure Rate	Mean Generic Failure Rate / Mean Generic Failure Rate
Shaft	0.62/0.15 = 4.13	0.35/0.15 = 2.33
Packing	1.12/0.25 = 4.50	0.7/0.25 = 2.80
Keys	0.28/0.08 = 3.50	0.14/0.08 = 1.75
Gaskets	0.225/0.05 = 4.50	0.138/0.05 = 2.76
Impeller	0.24/0.06 = 4.00	0.15/0.06 = 2.50
Gland	0.20/0.04 = 4.00	0.125/0.05 = 2.50
Casing Ring	0.16/0.04 = 4.00	0.10/0.04 = 2.50
Average Ratio	28.63/7 = 4.09	17.14/7 = 2.45

TABLE XII

PREDICTED GENERIC AND FIELD FAILURE RATES FOR 5x4 SK AND KSK PUMPS

GROUP NO.	Predicted Generic Failure Rates Min.	Mean	Max.	Application Factor K_A	Operating Factor K_{OP}	Design Group Factor K_G	Predicted Field Failure Rates Min.	Mean	Max.
I	1.51	7.34	13.61	1.23	6.20	1.18	13.6	66.1	122.5
II	1.51	7.34	13.61	1.17	7.00	1.55	19.2	93.2	172.9
III	1.51	7.34	13.61	1.11	5.90	1.00	9.9	48.1	89.2
IV	1.51	7.34	13.61	1.12	6.42	1.18	12.8	62.1	115.2
V	1.45	6.90	12.75	4.375	14.00	0.82	72.8	346.5	640.4
VI	1.45	6.90	12.75	1.28	16.00	0.63	18.7	89.0	164.5
VII	1.39	7.00	13.20	1.13	7.00	1.18	13.0	65.3	123.2
VIII	1.39	7.00	13.20	1.52	6.85	1.37	20.0	100.6	189.7

TABLE XIII

FIELD FAILURES, TOTAL HOURS OF OPERATION, AND FIELD FAILURE RATE FOR EACH GROUP

GROUP NO.	NO. OF FAILURES	HOURS	FIELD FAILURE RATE fr/10^6 Hour
I	11	345,548	31.8
II	14	427,654	32.8
III	2	258,005	11.6
IV	7	298,918	23.4
V	See Table XIV		115.0
VI	2	67,200	29.7
VII	4	166,428	24.2
VIII	3	90,022	33.4

TABLE XIV

PUMP FAILURES AND FAILURE RATE FOR GROUP V

Operating Hours Interval	Hours Accumulated By All Pumps During The Interval (T)	No. of Failures (f)	Failure Rate fr/10^6 Hours
0-1,000	80,109	22	274.8
1,000-2,000	58,572	6	102.3
2,000-3,000	50,605	6	118.5
3,000-4,000	47,659	9	188.9
4,000-5,000	37,829	4	105.8
5,000-6,000	33,000	4	121.1
6,000-7,000	32,949	5	151.8
7,000-8,000	31,583	3	95.0
8,000-9,000	30,308	5	165.0
9,000-10,000	18,887	2	106.0
10,000-11,000	15,654	1	64.0
11,000-12,000	15,000	1	66.7
12,000-13,000	14,113	1	70.8
13,000-14,000	13,263	1	75.5
14,000-15,000	12,552	1	79.6
15,000-16,000	12,000	2	166.8

Sample Calculation:

Interval: 0-1,000

$$\text{fr}/10^6 \text{ hrs. } (\lambda) = \frac{\text{No. of Failures (f)}}{\text{Hours accumulated by all pumps during the interval (T)}} = \frac{22}{80,109} = 274.8$$

TABLE XV

ACTUAL MANUFACTURER'S RELATIVE COSTS FOR 5x4 SK AND KSK PUMPS

No.	Manufacturer's Costs*	Units	Pump Groups							
			I	II	III	IV	V	VI	VII	VIII
1	Spec. Cost (Matrl., labor, burden)	Relative to Base	3.78	3.78	4.22	4.22	12.26	11.93	3.57	3.57
2	R&D Eng. (For Improvement)	Spec. %	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
3	Net Eng. Expense (Product Section)	Spec. %	5.9	5.9	5.9	5.9	6.2	6.2	5.9	5.9
4	Eng. Change During Mfg.	Spec. %	.4	.4	.4	.4	.4	.4	.4	.4
5	New Patterns (Repair + Storage)	Spec. %	2.9	2.0	2.0	2.0	1.0	1.0	2.0	2.0
6	Small Tools (Drills, Fixtures, etc.)	Spec. %	.5	.5	.5	.5	.4	.4	.5	.5
7	Adjusted Mfg. Burden (Correction)	Spec. %	3.9	3.9	4.6	4.6	9.8	8.8	3.6	3.6
8	Shipping Expense (Crate + Labor)	Spec. %	3.0	3.0	3.0	3.0	4.0	4.0	3.0	3.0
9	Miscellaneous (Variance Costs)	Spec. %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
10	Total % of Spec. Cost	in %	19.0	19.0	19.7	19.7	25.1	24.1	18.7	18.7
11	Total Relative Costs Added to Spec. Cost	Relative To Base	0.72	0.72	0.83	0.83	3.07	2.88	0.67	0.67
12	Manufacturer's Total Relative before shipment costs	Relative To Base	4.50	4.50	5.05	5.05	15.33	14.81	4.24	4.24

TABLE XV (continued

No.	Manufacturer's Costs*	Units	Pump Groups I	II	III	IV	V	VI	VII	VIII
13	After Shipment Costs (No-Charge or Goodwill and Warranty Costs)	Spec. %	1.6	2.1	2.6	0.5	0	0	0.2	3.8
14	Manufacturer's Total Relative After Shipment Costs	Relative To Base	0.061	0.080	0.067	0.021	0	0	0.007	0.136
15	Manufacturer's Total Cost	Relative To Base	4.561	4.580	4.117	4.071	15.33	14.81	4.247	4.377
16	Manufacturer's Selling Price**	Relative To Base	4.87	4.89	5.47	5.42	16.40	15.85	4.53	4.68

*Do not include costs which do not affect, or are not affected by, reliability.
**With 7% Fee as accepted by the Department of Defense.

TABLE XVI

ADJUSTED GROUP FAILURE RATES TO SHIPBOARD SEAWATER ENVIRONMENT

GROUP NO.	$\frac{(K_A\ K_{OP})\text{GROUP 5}}{(K_A\ K_{OP})\text{GROUP i}}$	ADJUSTED FAILURE RATE
I	8.05	256
II	7.50	246
III	9.34	79
IV	8.54	200
V*	1.00	115
VI	2.99	89
VII	7.76	188
VIII	5.90	197

$*K_A\ K_{OP})$GROUP 5 = 61.3

TABLE XVII

PRORATED PUMP INITIAL COST

GROUP	INITIAL COST/1000 HOURS
I	0.162
II	0.163
III	0.182
IV	0.181
V	0.547
VI	0.528
VII	0.151
VIII	0.156

TABLE XVIII

CUSTOMER'S RELATIVE COSTS FOR 5x4 SK and KSK PUMPS

	GROUP NO.							
Cost Item	I	II	III	IV	V	VI	VII	VIII
Purchase Price*	4.87	4.89	5.47	5.42	16.42	15.85	4.53	4.68
Unscheduled Replaced Parts**	0.0627	0.0398	0.015	0.0223	0.274	0.0219	0.0451	0.0488
Unscheduled Labor**	0.0192	0.0149	0.0049	0.0111	0.053	0.0107	0.0151	0.0141
Scheduled Replaced Parts**	0.0076	0.0190	0.0265	0.0019	1.02	0.8810	0	0.0111
Scheduled Labor**	0.0143	0.0104	0.0065	0.0015	0.094	0.1771	0	0.0094
Unsheduled Downtime Cost **	0.362	0.280	0.0925	0.209	0.995	0.201	0.283	0.264

* With 7% Fee as accepted by the Department of Defense

** Relative cost per pump per 1000 hour of operation

TABLE XIX

ADJUSTED CUSTOMER'S RELATIVE COSTS* FOR 5x4 SK and KSK PUMPS

	GROUP NO.							
Cost Item	I	II	III	IV	V	VI	VII	VIII
1. Purchase Price	0.162	0.163	0.182	0.181	0.547	0.528	0.151	0.156
2. Unscheduled Replaced Parts	0.505	0.300	0.140	0.191	0.274	0.065	0.350	0.289
3. Unscheduled Labor	0.155	0.112	0.046	0.095	0.053	0.032	0.117	0.083
4. Unscheduled Down-time Cost	2.92	2.11	0.865	1.78	0.995	0.602	2.20	1.56
Total Unscheduled Repair Costs	3.580	2.522	1.051	2.066	1.322	0.699	2.667	1.932
5. Scheduled Re-placed Parts	0.302	0.304	0.340	0.339	1.02	0.96	0.282	0.291
6. Scheduled Labor	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094
Total Scheduled Repair Cost	0.396	0.398	0.434	0.433	1.114	1.054	0.376	0.385
Total Customer Cost	4.138	3.083	1.667	2.680	2.983	2.281	3.194	2.473

* Relative cost per 1000 hours of pump operation

EFFECT OF LEVEL OF RELIABILITY ON THE MANUFACTURER'S TOTAL PRODUCT COST

R_{OM} = Optimum reliability for minimum manufacturer's selling price.

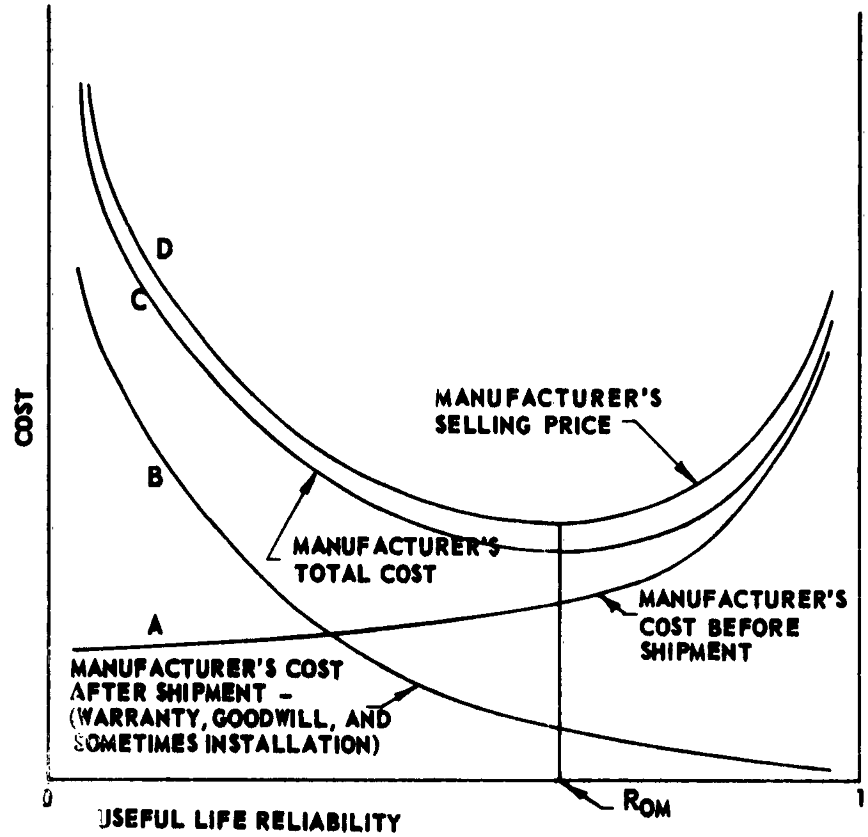


FIGURE 1

RELIABILITY AND THE CUSTOMER'S TOTAL COST PICTURE

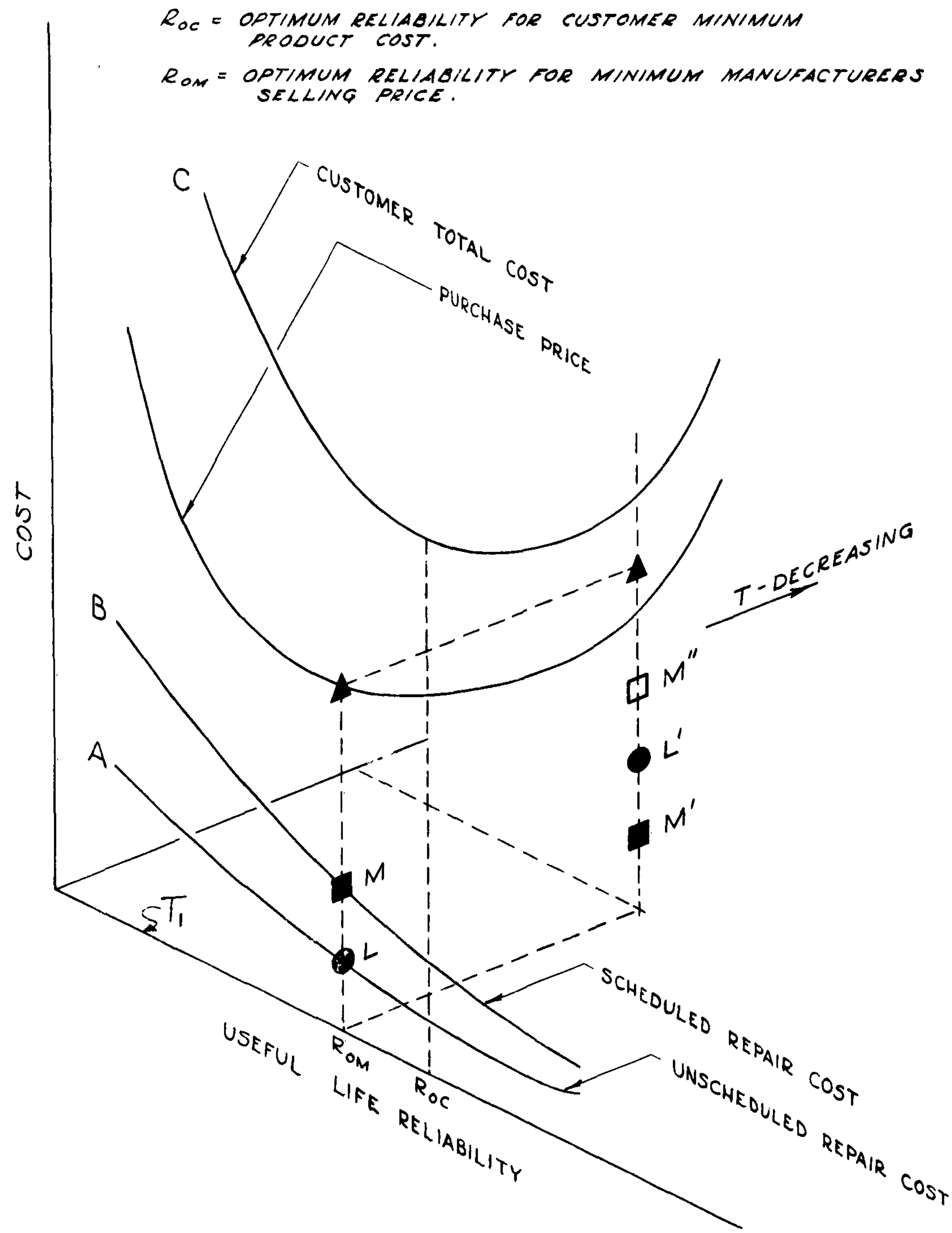


FIGURE 2

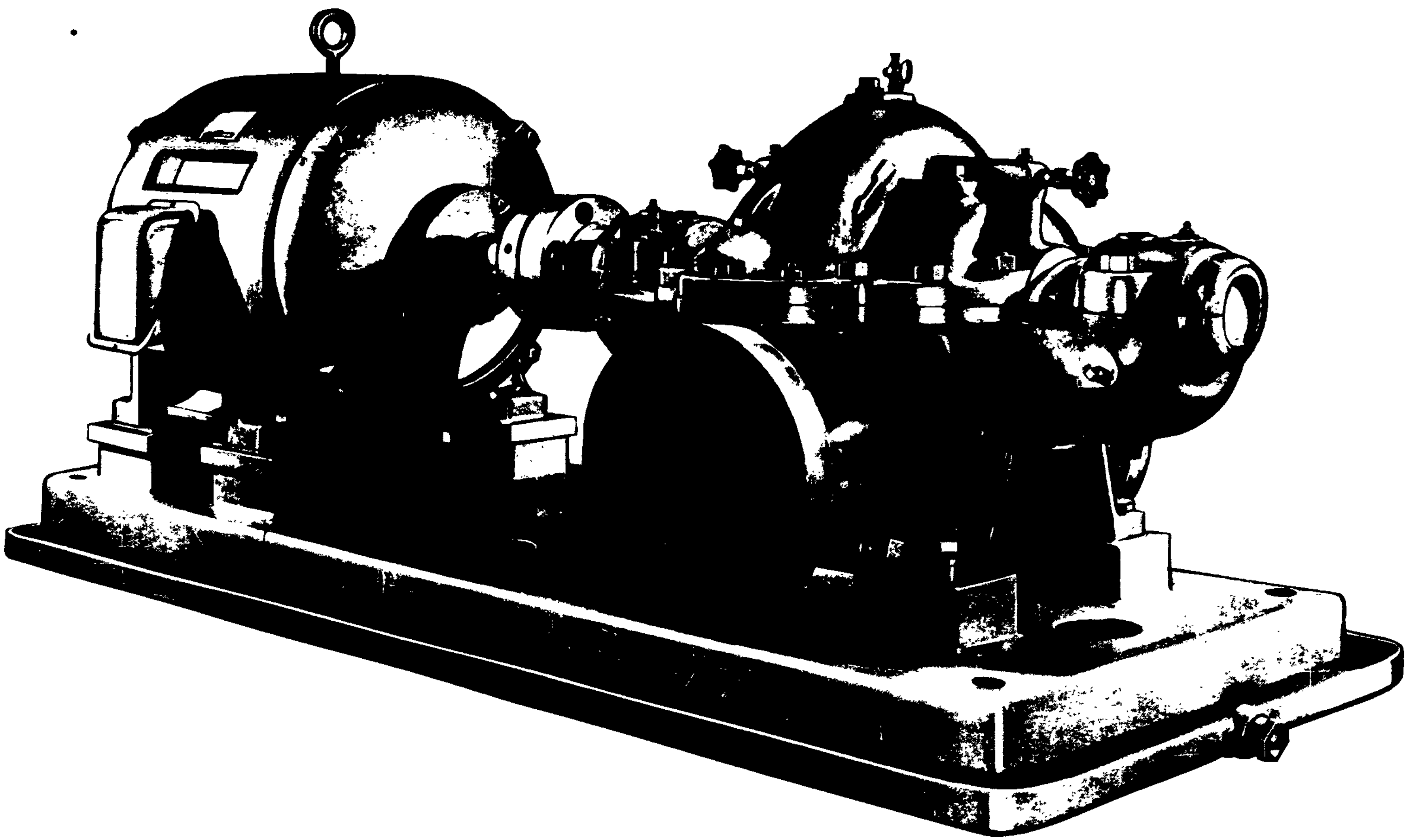


Figure 3

External view of 5 x 4 SK pump shown driven by a motor, both mounted on a bed plate.

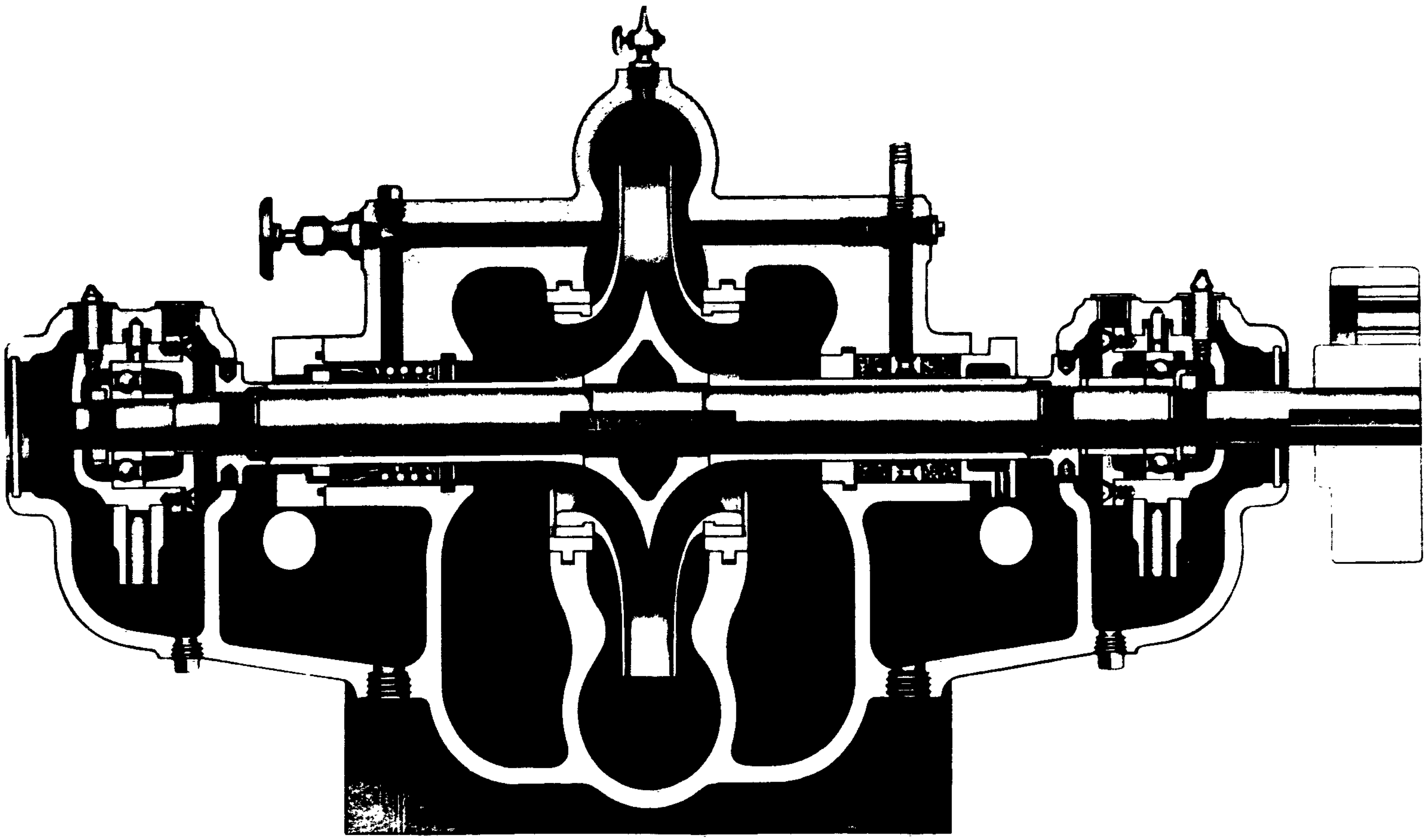


Figure 4
Sectional view of 5 x 4 SK pump showing both mechanical seal and packing.

Allis-Chalmers Manufacturing Co.

CENTRIFUGAL PUMP RELIABILITY REPORT

Type KSK, 5x4, single stage, double suction, split casing pump

Customer__________

Customer Order No.__________

Shop Order No.__________

Shipping Order No.__________

Pump Serial No.__________

District Office__________

Date Shipped__________

Type Bearings__________

Speed__________

Impeller Dia.__________

Driver__________

Replaced or Repaired Part		Date Part Replaced or Repaired	Amount of Running Time on Replaced Part - Hrs.	Reason for Replacement or Repair. If Wear, Estimate Amount of Wear, If Repair, Describe
Size & Name	Part No.			

Check one of following:

Average Pump operation per day	4 Hr ☐	8 Hr. ☐	16 Hr ☐	24 Hr ☐
% Impurities in pumped fluid	0%-- ☐	5%-- ☐	10%-- ☐	More ☐
No. of stops per day	0--- ☐	2--- ☐	10--- ☐	More ☐
Operation near shutoff	Never ☐	On Occ. ☐	Freq. ☐	
Pump operation (variation from rating)	5% ☐	15% ☐	35%-- ☐	More ☐

Date Placed in operation__________

Description of fluid being pumped:__________

Suction pressure:__________

Customer comments:__________

Downtime - cost/hr__________

(See other side for instructions)

FIGURE 5

FIGURE 5 (Continued)

INSTRUCTIONS

Complete as much of the report as possible using estimates if necessary.

List all parts that have been replaced or repaired on the pump identified by serial number at the top of the page.

Estimate the running time on replaced or repaired parts.

Give reason for replacement or repair of each part. Give an estimate of the amount of wear in terms of changes in dimensions or tolerances where applicable. Briefly describe repairs made.

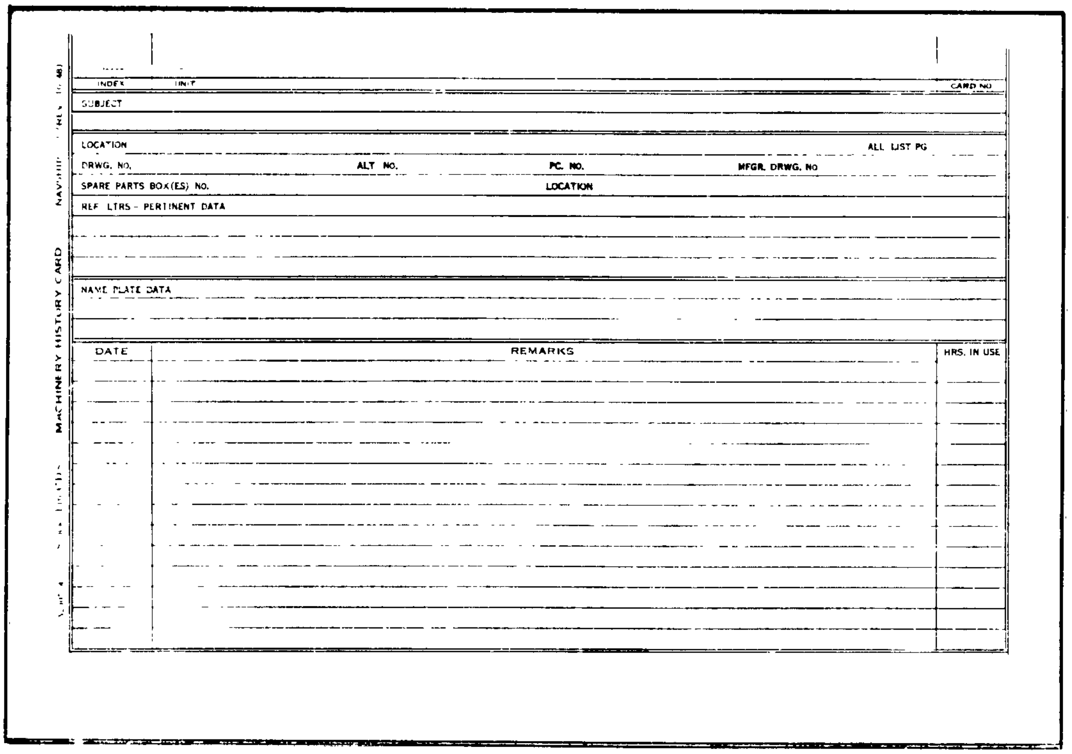
Give the approximate operating range or variation from the rated point for the pump by checking the appropriate box.

Under "Comments" estimate total hours of pump operation, indicate vibration and noise levels and describe any unusual operating or environmental condition.

Under "Downtime" give cost/hour if the function of the pump is not performed due to pump failure, i.e., what would be the total cost of a pump failure due to loss of production, etc., if there were not any standby pumps. If a standby pump is used for emergencies, give its total cost per year.

MACHINERY HISTORY CARD

FORM NAVSHIP-527


NAVSHIP ... MACHINERY HISTORY CARD

INDEX | UNIT | CARD NO

SUBJECT

LOCATION | ALL LIST PG

DRWG. NO. | ALT NO. | PC. NO. | MFGR. DRWG. NO

SPARE PARTS BOX(ES) NO. | LOCATION

REF LTRS - PERTINENT DATA

NAME PLATE DATA

DATE	REMARKS	HRS. IN USE

FIGURE 6

REPORT OF EQUIPMENT FAILURE
FORM NAVSHIPS-3621

REPORT OF EQUIPMENT FAILURE
NAVSHIPS 3621 (REV. 6-60)

REPORT BUSHIPS—9130-1

1. SHIP TYPE	2. HULL NUMBER	3. DATE OF FAILURE (MONTH, DAY, YEAR)	4. DATE OF LAST FAILURE (MONTH, DAY, YEAR)

NAME OF FAILED COMPONENT	5. COMPONENT ALLOWANCE GROUP NUMBER
	6. COMPONENT IDENTIFICATION NO. (CID)
COMPONENT MANUFACTURER'S NAME	7. MANUFACTURE SERIAL NUMBER

8. NUMBER OF MAINTENANCE CHECKS SINCE LAST FAILURE	9. DID COMPONENT FAIL IN OPERATION? ☐ YES ☐ NO	10. OPERATIONAL HOURS SINCE COMPONENT LAST FAILURE

CAUSE OF FAILURE (CHECK ONE)

1. ☐ BROKEN OR CRACKED PART	5. ☐ FAILURE OF WELD	9. ☐ LOOSE CONNECTION	13. ☐ LEAK
2. ☐ EXCESSIVE PART CLEARANCE	6. ☐ LACK OF LUBRICATION	10. ☐ INSULATION FAILURE	14. ☐ FUNGUS
3. ☐ FAILURE OF CONTROL	7. ☐ IMPROPERLY INSTALLED	11. ☐ WATER	15. ☐ CORROSION
4. ☐ FOREIGN MATTER	8. ☐ EXCESSIVE HEAT	12. ☐ VIBRATION	16. ☐ UNKNOWN

17. ☐ OTHER (SPECIFY)

PART DATA

NAME OF PART THAT FAILED	MATERIAL OF WHICH PART IS MADE	HOURS OPERATIVE	PART NO. (Use Only One. Federal Stock No., Bureau Plan & Piece No., or Mfg. No.)

REMARKS AND RECOMMENDATIONS

GIVE DESCRIPTION OF FAILURE. ELABORATE ON CAUSE AND/OR REMEDY APPROPRIATE. GIVE RECOMMENDATIONS TO PREVENT RECURRENCE OF FAILURE:

SIGNED	DATE

FIGURE 7

Curves show approximately the characteristics when pumping clear water with specific gravity of 1.0. No guarantee is made except for the rated point.

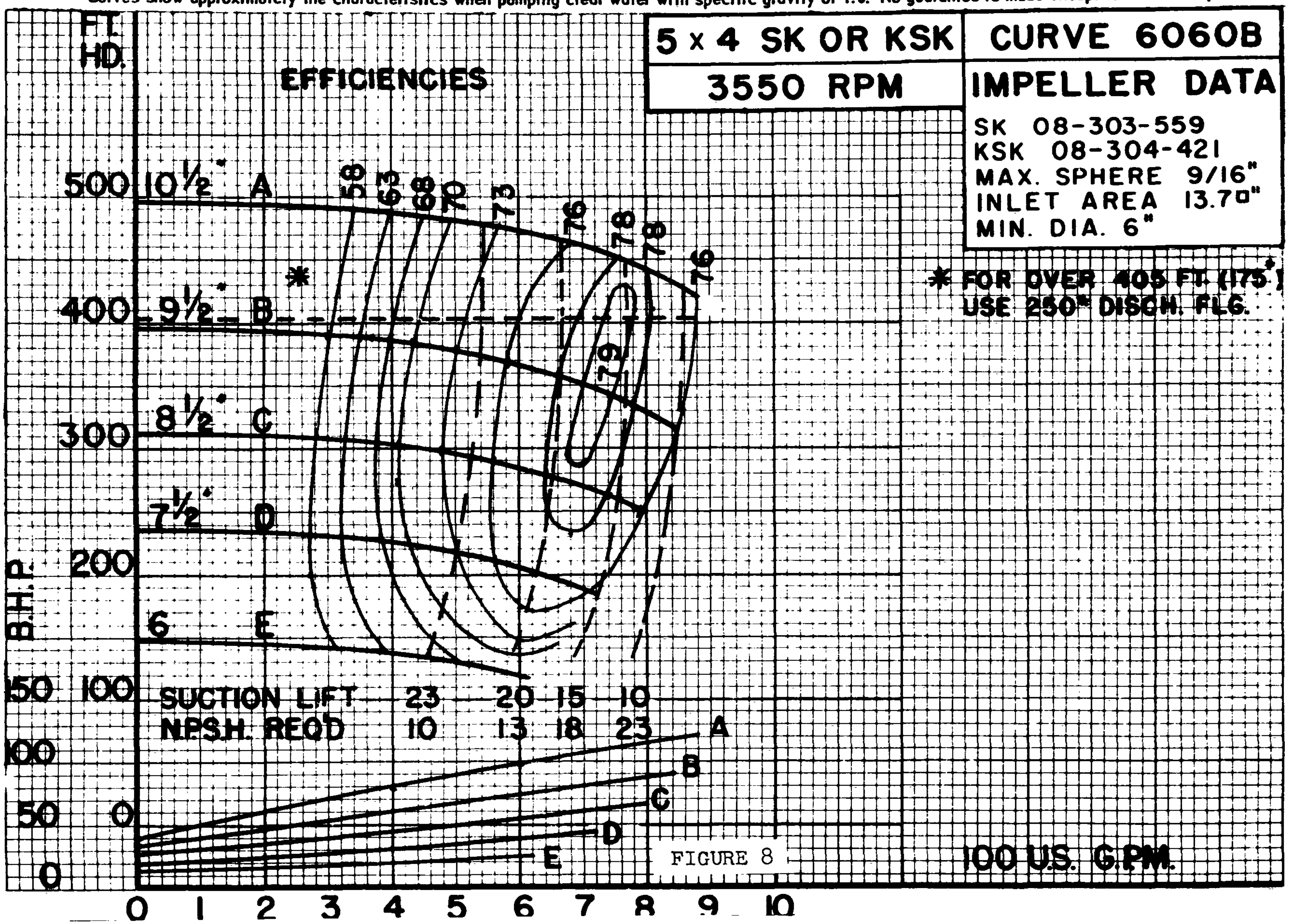


FIGURE 8

ALLIS-CHALMERS MFG. CO.

ITEM NO.

Curves show approximately the characteristics when pumping clear water with specific gravity of 1.0. No guarantee is made except for the rated point.

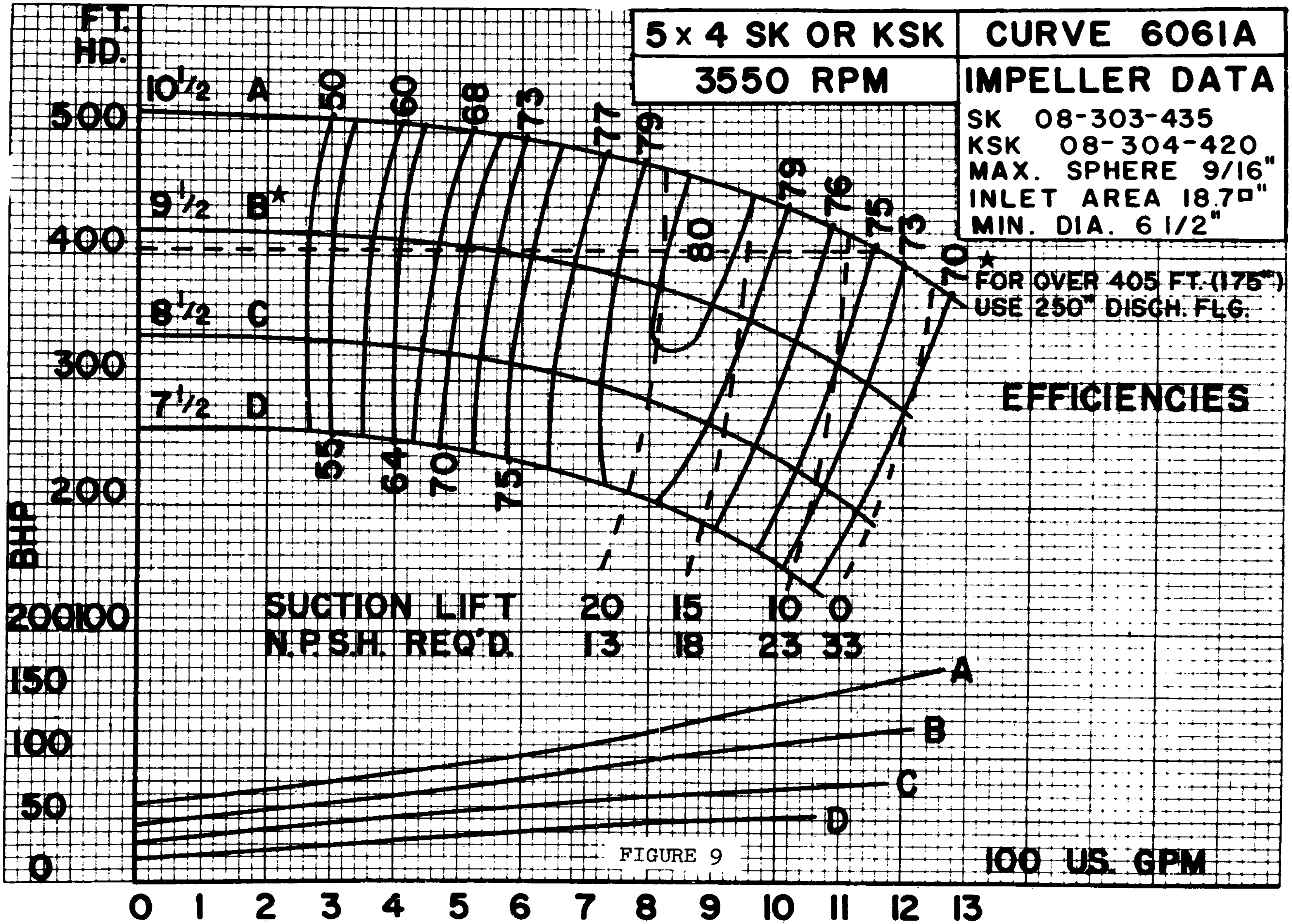


FIGURE 9

ALLIS-CHALMERS MFG. CO.

ITEM NO.

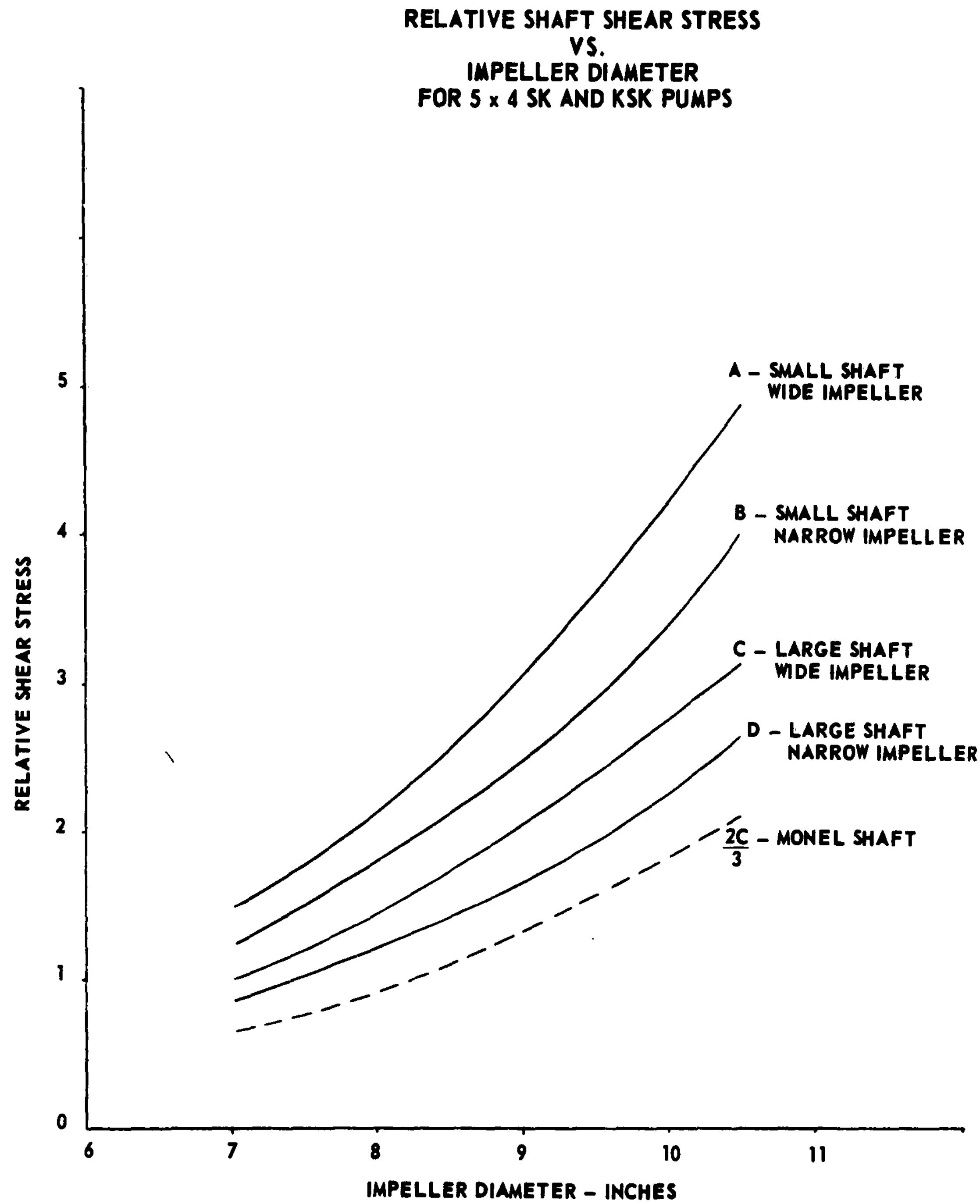

RELATIVE SHAFT SHEAR STRESS
VS.
IMPELLER DIAMETER
FOR 5 x 4 SK AND KSK PUMPS
RELATIVE SHEAR STRESS
0
1
2
3
4
5
6
7
8
9
10
11
IMPELLER DIAMETER – INCHES
A – SMALL SHAFT WIDE IMPELLER
B – SMALL SHAFT NARROW IMPELLER
C – LARGE SHAFT WIDE IMPELLER
D – LARGE SHAFT NARROW IMPELLER
2C/3 – MONEL SHAFT

FIGURE 10

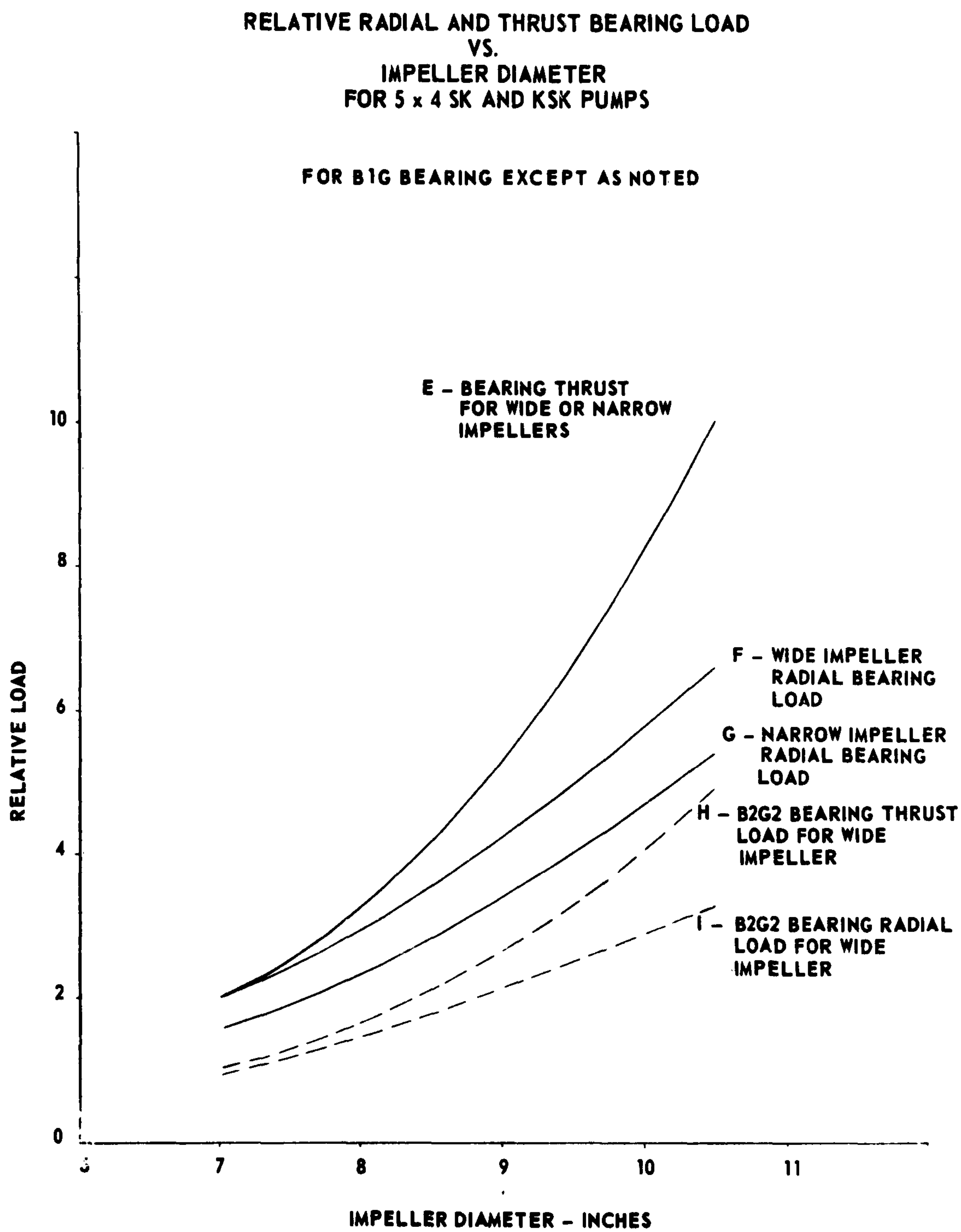

RELATIVE RADIAL AND THRUST BEARING LOAD
VS.
IMPELLER DIAMETER
FOR 5 x 4 SK AND KSK PUMPS
FOR B1G BEARING EXCEPT AS NOTED
E – BEARING THRUST FOR WIDE OR NARROW IMPELLERS
F – WIDE IMPELLER RADIAL BEARING LOAD
G – NARROW IMPELLER RADIAL BEARING LOAD
H – B2G2 BEARING THRUST LOAD FOR WIDE IMPELLER
I – B2G2 BEARING RADIAL LOAD FOR WIDE IMPELLER
RELATIVE LOAD
0
2
4
6
8
10
7
8
9
10
11
IMPELLER DIAMETER – INCHES

FIGURE 11

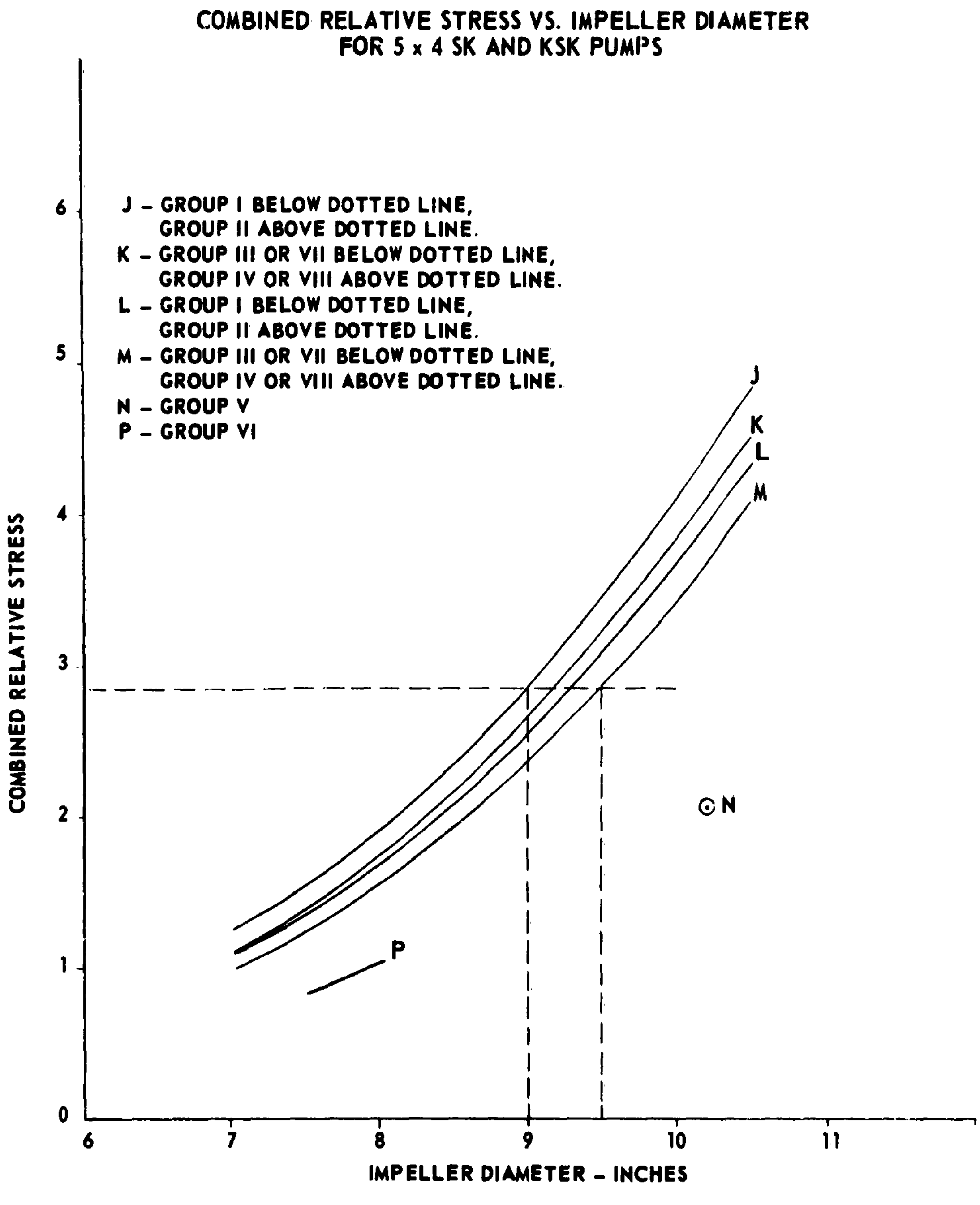

COMBINED RELATIVE STRESS VS. IMPELLER DIAMETER
FOR 5 x 4 SK AND KSK PUMPS
J - GROUP I BELOW DOTTED LINE, GROUP II ABOVE DOTTED LINE.
K - GROUP III OR VII BELOW DOTTED LINE, GROUP IV OR VIII ABOVE DOTTED LINE.
L - GROUP I BELOW DOTTED LINE, GROUP II ABOVE DOTTED LINE.
M - GROUP III OR VII BELOW DOTTED LINE, GROUP IV OR VIII ABOVE DOTTED LINE.
N - GROUP V
P - GROUP VI
COMBINED RELATIVE STRESS
IMPELLER DIAMETER - INCHES
0
1
2
3
4
5
6
7
8
9
10
11
J
K
L
M
N
P

FIGURE 12

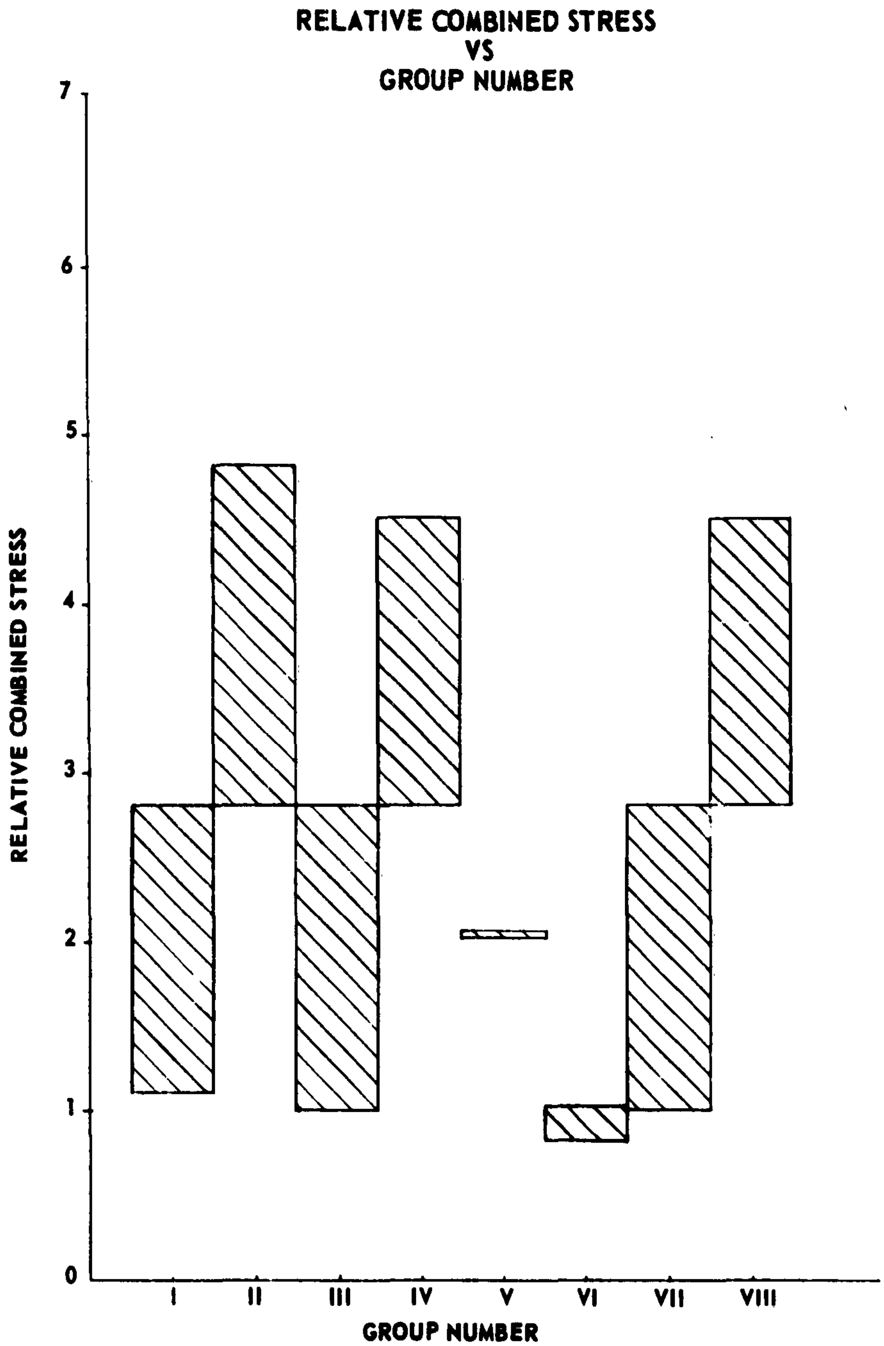

RELATIVE COMBINED STRESS
VS
GROUP NUMBER
RELATIVE COMBINED STRESS
0
1
2
3
4
5
6
7
I
II
III
IV
V
VI
VII
VIII
GROUP NUMBER

FIGURE 13

REPORTED FAILURE RATES FOR COMPONENT PARTS IN DIFFERENT INSTALLATION ENVIRONMENTS

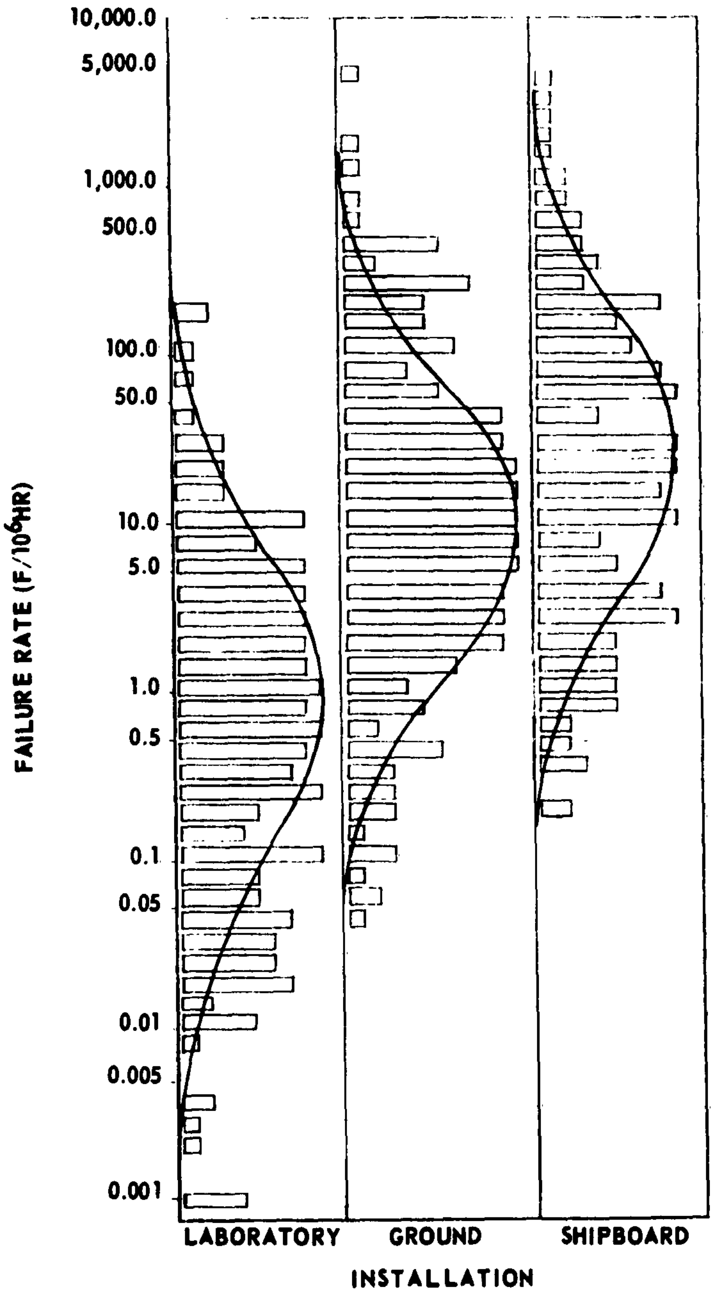


FIGURE 14

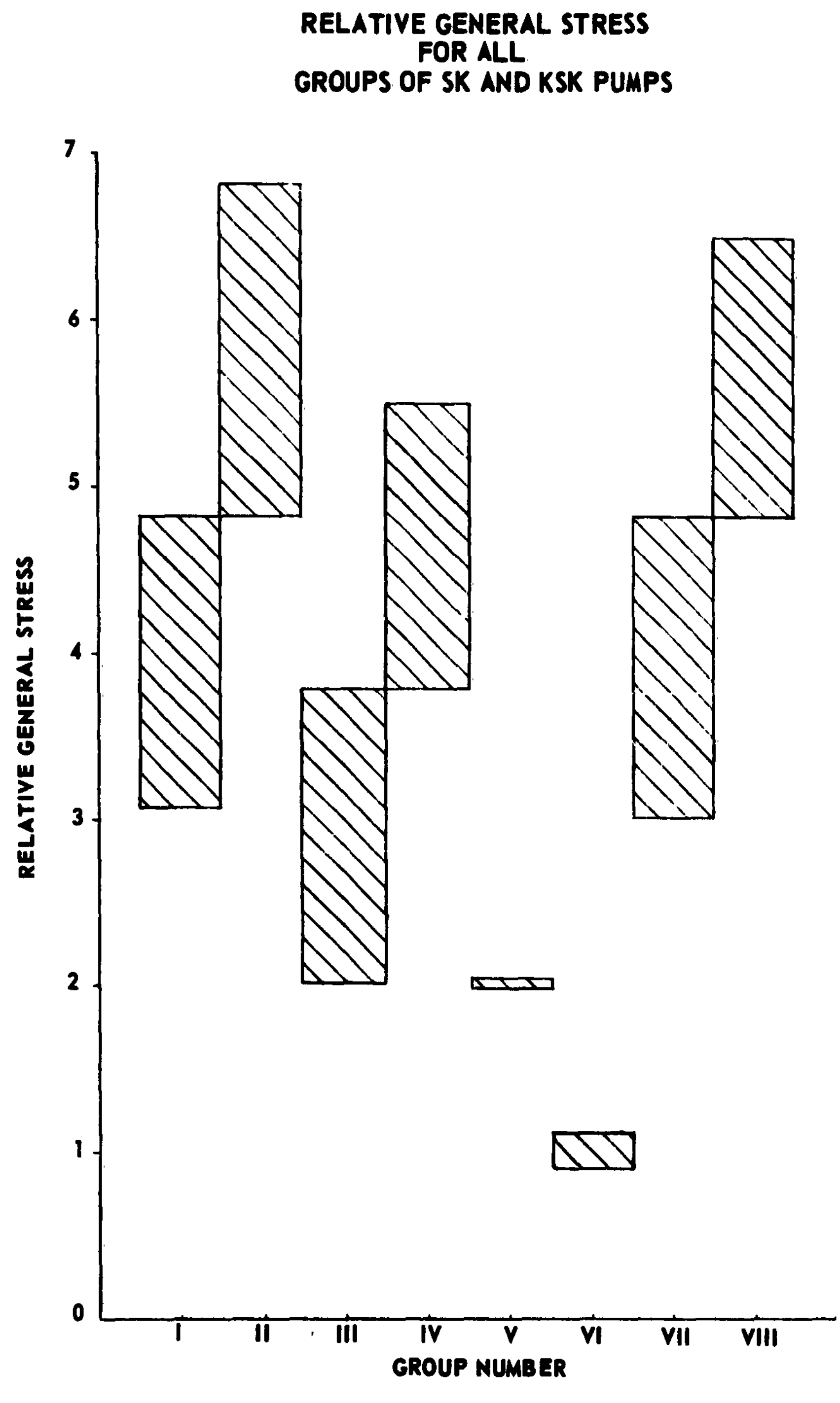
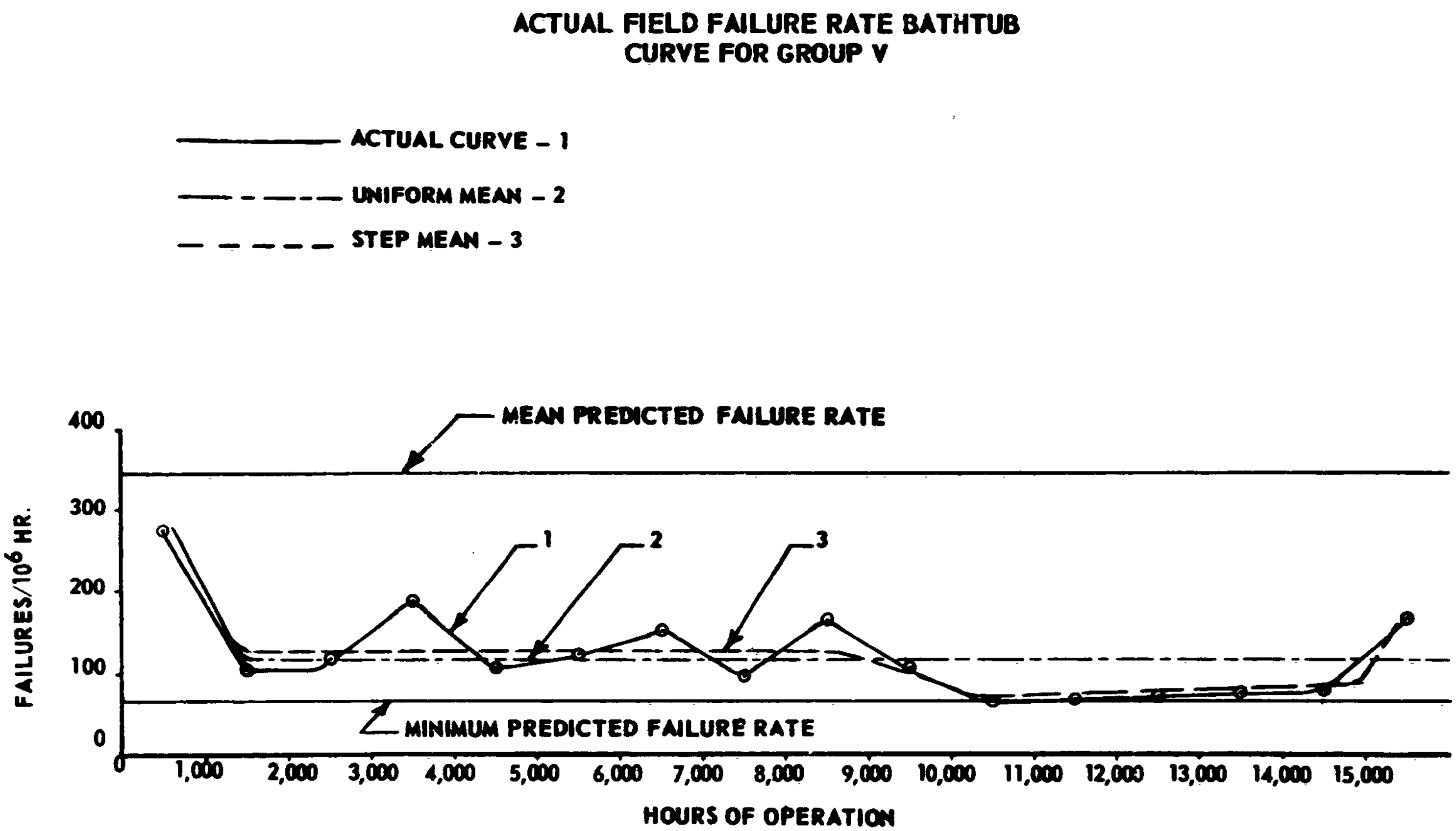

RELATIVE GENERAL STRESS
FOR ALL
GROUPS OF SK AND KSK PUMPS
RELATIVE GENERAL STRESS
7
6
5
4
3
2
1
0
I
II
III
IV
V
VI
VII
VIII
GROUP NUMBER

FIGURE 15



ACTUAL FIELD FAILURE RATE BATHTUB
CURVE FOR GROUP V
ACTUAL CURVE – 1
UNIFORM MEAN – 2
STEP MEAN – 3
MEAN PREDICTED FAILURE RATE
MINIMUM PREDICTED FAILURE RATE
1
2
3
400
300
200
100
0
FAILURES/10⁶ HR.
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
HOURS OF OPERATION

FIGURE 16

ACTUAL AND PREDICTED GROUP FAILURE RATE
HISTOGRAM

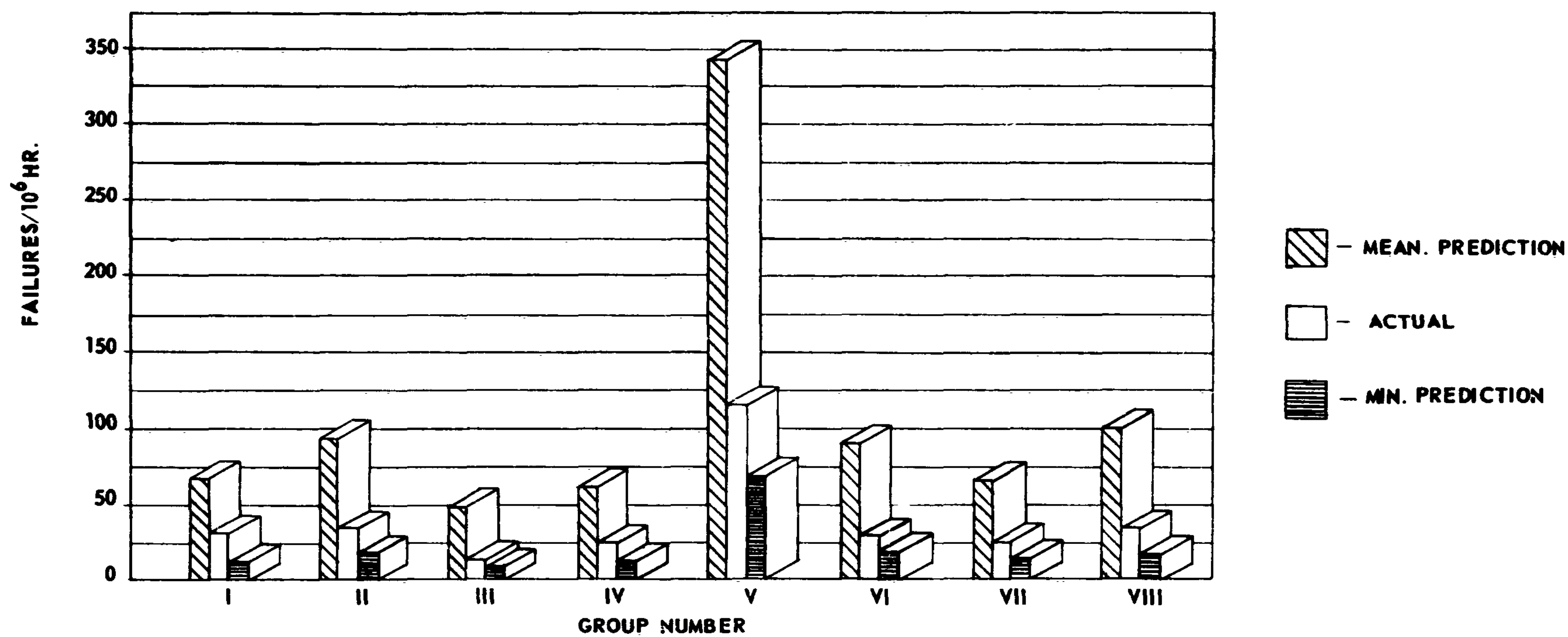


FIGURE 17

ALLIS-CHALMERS MATERIAL REQUISITION TICKET

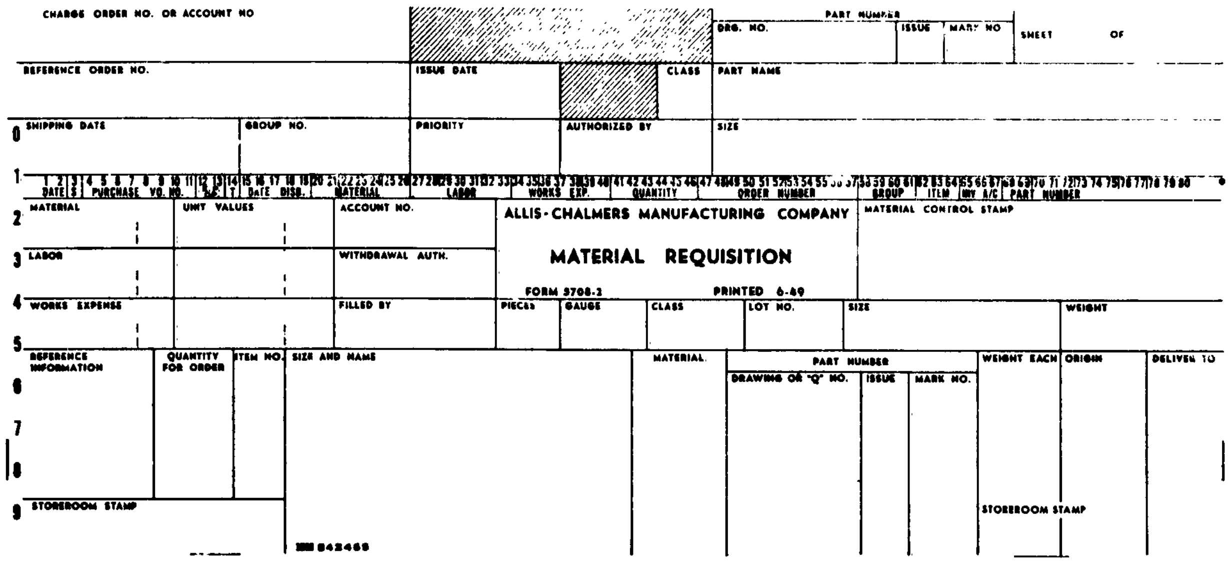

CHARGE ORDER NO. OR ACCOUNT NO
PART NUMBER
DRG. NO. | ISSUE | MARK NO | SHEET OF
REFERENCE ORDER NO.
ISSUE DATE
CLASS
PART NAME
SHIPPING DATE
GROUP NO.
PRIORITY
AUTHORIZED BY
SIZE
DATE | PURCHASE VO. NO. | DATE DISB. | MATERIAL | LABOR | WORKS EXP. | QUANTITY | ORDER NUMBER | GROUP | ITEM | PART NUMBER
MATERIAL
UNIT VALUES
ACCOUNT NO.
ALLIS-CHALMERS MANUFACTURING COMPANY
MATERIAL CONTROL STAMP
LABOR
WITHDRAWAL AUTH.
MATERIAL REQUISITION
FORM 5708-2
PRINTED 6-49
WORKS EXPENSE
FILLED BY
PIECES | GAUGE | CLASS | LOT NO. | SIZE | WEIGHT
REFERENCE INFORMATION | QUANTITY FOR ORDER | ITEM NO. | SIZE AND NAME | MATERIAL | PART NUMBER | WEIGHT EACH | ORIGIN | DELIVER TO
DRAWING OR "Q" NO. | ISSUE | MARK NO.
STOREROOM STAMP
STOREROOM STAMP
842469

FIGURE 18

ALLIS-CHALMERS LABOR TICKET

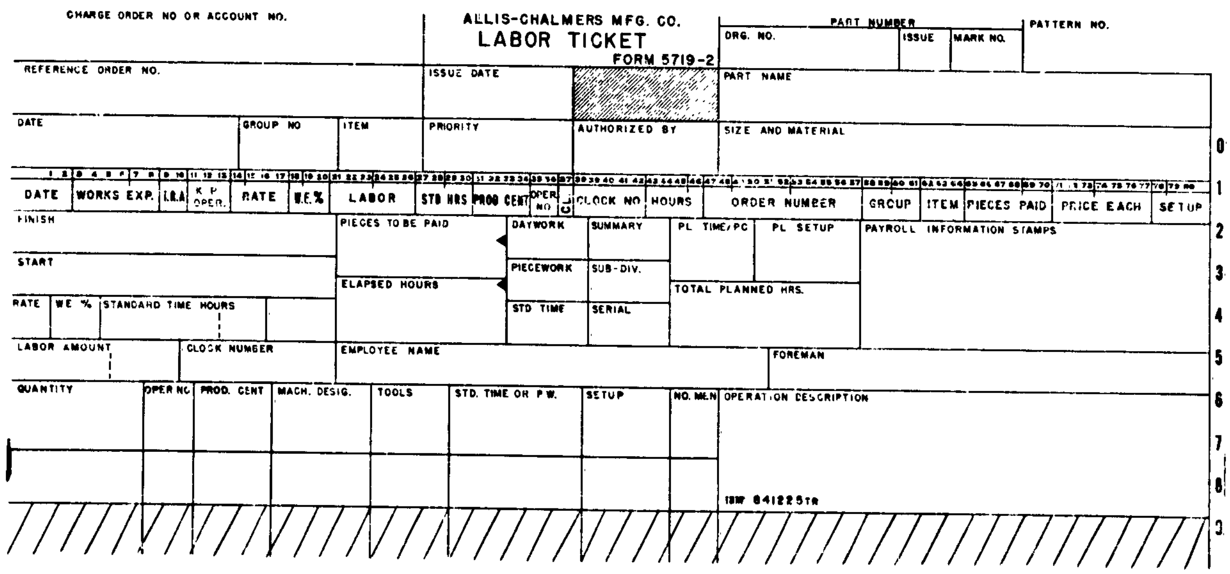

CHARGE ORDER NO OR ACCOUNT NO.
ALLIS-CHALMERS MFG. CO.
LABOR TICKET
FORM 5719-2
PART NUMBER
DRG. NO. | ISSUE | MARK NO.
PATTERN NO.
REFERENCE ORDER NO.
ISSUE DATE
PART NAME
DATE | GROUP NO | ITEM | PRIORITY | AUTHORIZED BY | SIZE AND MATERIAL
DATE | WORKS EXP. | I.B.A | K.P. OPER. | RATE | W.E.% | LABOR | STD HRS | PROD CENT | OPER NO | CLOCK NO | HOURS | ORDER NUMBER | GROUP | ITEM | PIECES PAID | PRICE EACH | SETUP
FINISH
PIECES TO BE PAID
DAYWORK | SUMMARY | PL TIME/PC | PL SETUP | PAYROLL INFORMATION STAMPS
START
PIECEWORK | SUB-DIV.
ELAPSED HOURS
TOTAL PLANNED HRS.
RATE | WE % | STANDARD TIME HOURS
STD TIME | SERIAL
LABOR AMOUNT | CLOCK NUMBER | EMPLOYEE NAME | FOREMAN
QUANTITY | OPER NO | PROD. CENT | MACH. DESIG. | TOOLS | STD. TIME OR P.W. | SETUP | NO. MEN | OPERATION DESCRIPTION
841225

FIGURE 19

ALLIS—CHALMERS MFG. CO.

COST REPORT

FORM 7586—1

QUANTITY PART NUMBER DATE

GROUP	ITEM	PROD'N. CENTER	OPER.	CL.	QUANTITY	ELAPSED HOURS	MATERIAL		LABOR	BURDEN		SET—UP	ORDER NUMBER AND/OR SPEC. COST
							CODE	AMOUNT		MANUFACTURING	MATERIAL		

FIGURE 20

RELIABILITY AND MANUFACTURER'S COST
FOR A 5 x 4 SK AND KSK PUMP
(SHIPBOARD SALTWATER ENVIRONMENT)

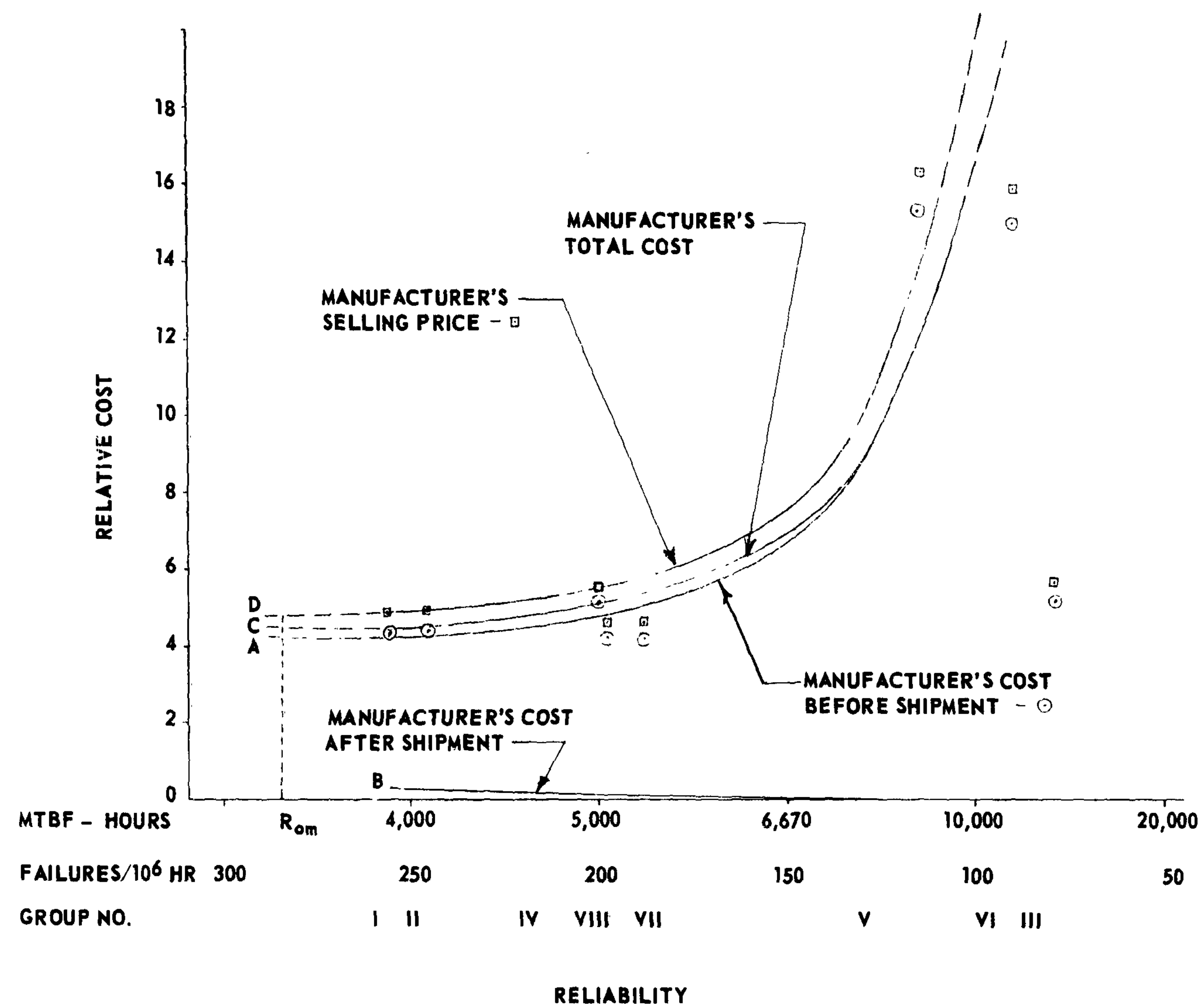


FIGURE 21

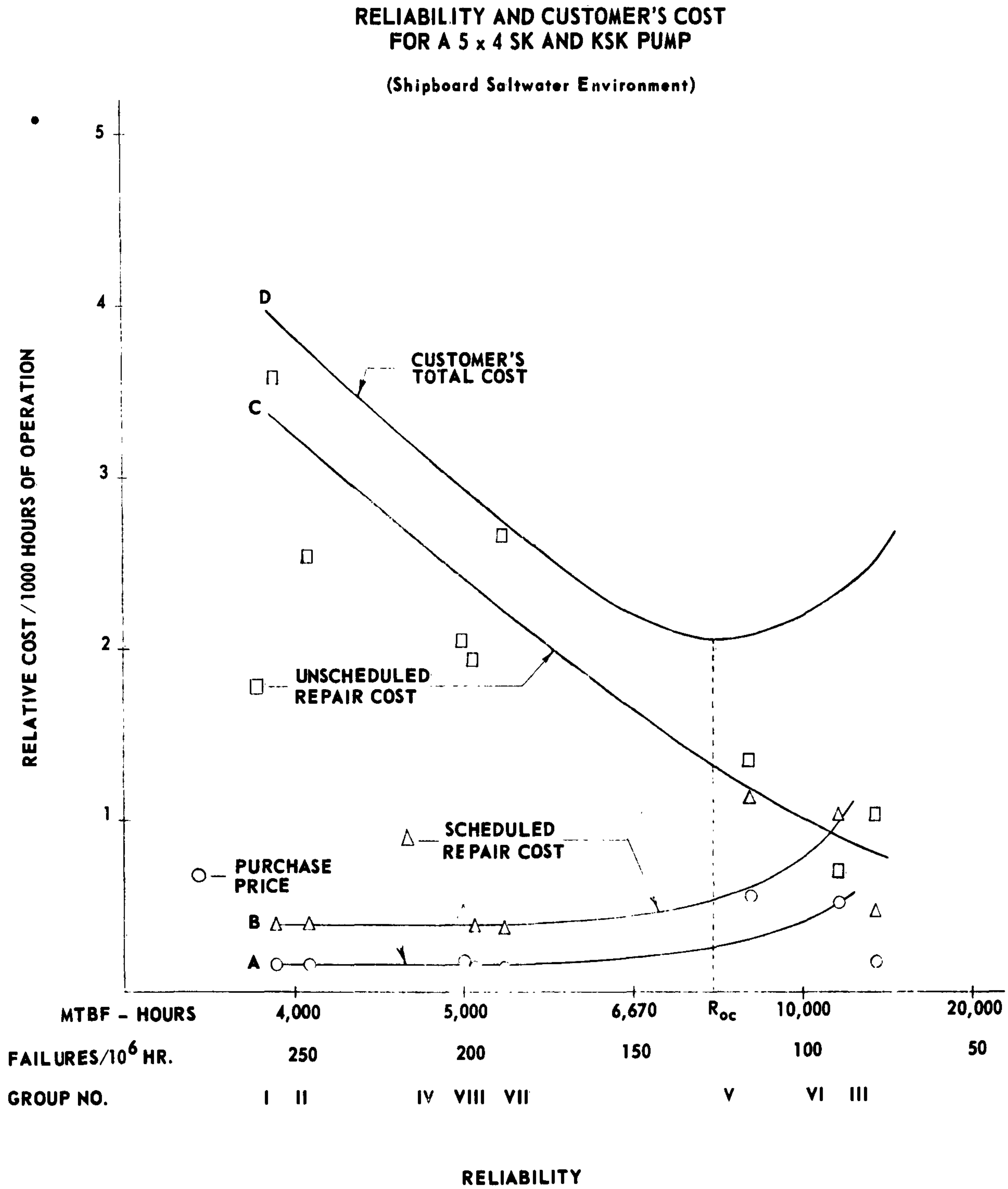

RELIABILITY AND CUSTOMER'S COST
FOR A 5 x 4 SK AND KSK PUMP
(Shipboard Saltwater Environment)
RELATIVE COST / 1000 HOURS OF OPERATION
5
4
3
2
1
D
C
B
A
CUSTOMER'S TOTAL COST
UNSCHEDULED REPAIR COST
SCHEDULED REPAIR COST
PURCHASE PRICE
MTBF - HOURS
4,000
5,000
6,670
R_{oc}
10,000
20,000
FAILURES/10^6 HR.
250
200
150
100
50
GROUP NO.
I
II
IV
VIII
VII
V
VI
III
RELIABILITY

FIGURE 22

CUSTOMER RELATIVE TOTAL COST FOR NEGLIGIBLE DOWNTIME COST

(Shipboard Saltwater Environment)

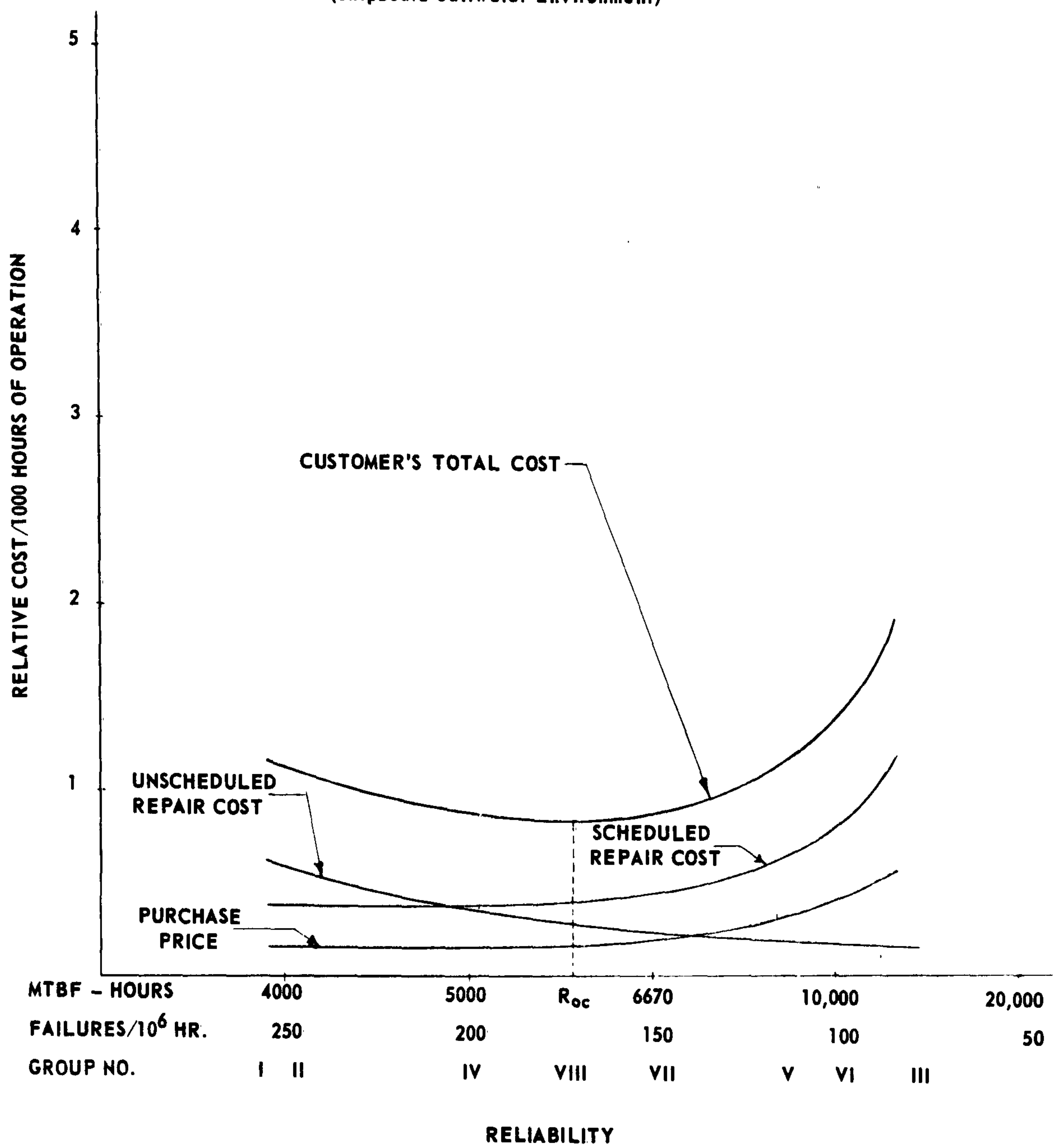


FIGURE 23

APPENDIX

Field, Repair and Maintenance Data

Detailed Field repair and maintenance data on the eight groups studied is presented in detail in the following tables. The numbers in the column entitled "Maintenance Action" identify the parts replaced during the maintenance action. Corresponding numbers and part names are shown in the "List of 5x4 SK and KSK Centrifugal Pump Components".

The data in the tables summarizes the information on the Machinery History Cards, Centrifugal Pump Reliability Reports, and spare parts data used in the determination of reliability and customer's cost in this study.

LIST OF 5x4 SK AND KSK CENTRIFUGAL PUMP COMPONENTS

Item No.	Component Name
1	Shaft
2	Shaft Sleeve
3	Shaft Nut R.H.
4	Shaft Nut L.H.
5	Casing Ring
6	Casing Bushing
7	Ball Bearing Adapter (O.E.)
8	Adapter Cap (O.E.)
9	Spacer Sleeve (O.E.)
10	Ball Bearing (O.E.)
11	Bearing End Plate Style #1
12	Bearing Lock Washer
13	Bearing Lock Nut
14	Ball Bearing Adapter (C.E.)
15	Adapter Cap (C.E.)
16	Spacer Sleeve (C.E.)
17	Ball Bearing (C.E.)
18	Bearing Lock Washer
19	Bearing Lock Nut
20	Alemite Fitting
21	Straight Key
22	Step Key
23	"O" Ring
24	Impeller
25	Impeller Ring

Item No.	Component Name
26	Machine Screw
27	Lock Washer
28	Rotating Assembly
29	Casing - Upper Half
30	Casing - Lower Half
31	Bearing End Plate Style #2
32	Gland-Half
33	Gland Bolt
34	Seal Cage
35	Oil Hole Cover
36	Alemite Collar
37	Valve Stem
38	Packing
39	Gasket - Suction
40	Gasket - Discharge
41	Straight Dowel
42	Pipe Plug
43	Aircock Tee Handle
44	S.F. Hex. Nut
45	Drive Screw
46	Casing Gasket
47	Hex. Setscrew
48	Crankcase Sealer
49	Bearing Cap
50	#0 Taper Dowel
51	#1 Taper Dowel
52	Cap Screw
53	Coupling Lock Nut

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
I	1	8	Raw Water	0	On Occasion	5	Replaced - 2	Preventive Maintenance	6-59
	2	8	Well Water	0	Never	5	Replaced - 29	Breakage	1-62
	3	24	City Water	10	Never	0	Replaced - 10, 11	Preventive Maintenance	6-54
	4	-	-	-	-	-	Replaced - 29, 28, 1, 24, 34	Breakage and Maintenance	-
	5	8	River Water	5	On Occasion	5	Replaced - 24, 5 Replaced - 25 Replaced - 2 Replaced - 2 Replaced - 2, 1, 25, 5, 24	Worn out Worn out Worn out Worn out Worn out	12-55 10-57 6-54 10-57 6-60
	6	24	Hot Water	0	Never	35	Replaced - 10, 17 Replaced - 1, 2	Worn out Worn out	5-58 [illegible]-60
	7	24	Hot Water	0	Never	35	Replaced - 2 Replaced - 24, 5, 25, 6, 2, 23,34, 3, 4	Worn out Worn out	8-55 1-57
	8	16	Warm Water	0	On Occasion	over 35	None	Internal Inspection	2-55
	9	16	Warm Water	0	On Occasion	over 35	None	Internal Inspection	2-55

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
I cont.	10	-	-	-	-	-	Replaced - 24, 5, 2,23, 3, 4, 45	Worn out	5-57
	11	16	Well Water	5	On Occasion	5	Replaced - 25, 10, 17	Worn out	8-54
	12	8	Clear Water	0	Frequently	15	Replaced - 2	Worn out	1-57
							" - 25	Worn out	4-58
							" - 24, 1, 21, 22	Worn out	7-58
							" - 25	Worn out	4-61
							" - 1, 2	Worn out	3-61
							" - 51	Broken	9-61
	13	8	River Water	5	On Occasion	over 35	Replaced - 24,1,2,5,10, 17	Corrosion	7-58
	14	-	-	-	-	-	Replaced - 1,21,22,2. 3,4		2-57
							Replaced - 24,5,1,21, 22,6,2,23, 34,3,4	Worn out	9-60
							Replaced - 24,5,1,21, 22,6,2	Worn out	2-61
							Replaced - 12,18,32,9, 16	Worn out	2-61
							Replaced - 24		8-61
	15	-	-	-	-	-	Replaced - 5,24,1,6,2, 23,34,32,33,3, 4,10,17,13,19	Worn out	11-60
							Replaced - 24	Worn out	8-62

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
II	1	24	Hot Water	0	On Occasion	35	Replaced - 24, 1, 2	Worn out	3-58
	2	-	-	-	-	-	Replaced - 2,5,25	Worn out	10-54
							Replaced - 1,21,22	Worn out	2-54
							Replaced - 24	Worn out	2-55
							Replaced - 1	Worn out	7-56
	3	16	Warm Water	0	On Occasion	over 35	Replaced - 10,17	Worn out	4-55
							Replaced - 10,17,24,25	Worn out	2-61
	4	4	Crude Oil	5	On Occasion	5	None	None	2-53
	5	4	Crude Oil	5	On Occasion	5	None	None	2-53
	6	-	-	-	-	-	Replaced - 2,10,17,12 18	Worn out	6-56
							Replaced - 24,1,21,22, 4	Worn out	8-61
	7	4	Refin-ed Oil	0	-	5	Replaced 5,10,17	Worn out	6-55
	8	24	Clear Water	0	Never	15	Replaced 24, 25	Worn out	9-57
							Replaced 1,2,21,22,5	Worn out	9-61
	9	8	Clear Water	0	Never	5	Replaced 1,2,24,25	Worn out	8-54
							Replaced 2,23	Worn out	8-62
	10	-	-	-	-	-	Replaced 25,6,2,10,17, 13,19	Worn out	4-54

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
II cont.	11	-	-	-	-	-	Replaced 10,17,25,1,21 22	Worn out	6-54
	12	16	Water	0	On Occasion	15	Replaced 1,2,10,17,23	Worn out	10-62
	13	16	Water	0	Never	15	Replaced - 1 Replaced - 29 Replaced - 29	Worn out Cracked Cracked	6-55 5-56 1-57
	14	-	-	-	-	-	Replaced 1,2,21,22,24, 25,10,17	Worn out	2-60
	15	-	-	-	-	-	Replaced 5,25,2,23	Worn out	8-60
	16	2	Water	0	Never	5	Replaced - 38	Worn out	7-62
	17	24	Water	10	On Occasion		None	-	4-62
III	1	8	Water	0	Never	15	Replaced - 2	Leadite from suction line caused wearout	6-57
	2	24	Con-densate	0	Never	35	Replaced - 2	Worn	7-62
	3	24	Conden-sate	0	Never	35	-	-	-
	4	-	-	-	-	-	Replaced 24, 25 Replaced - 2	Wear Worn	6-58 7-61

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
III cont.	5	-	-	-	-	-	Replaced 2,10,17,23,24, 25,38,39,40	Preventive Maintenance	10-59
	6	-	-	-	-	-	Replaced 1, 24,25,28	Preventive Main-	1-59
	7	12	River Water	-	Never	5	Replaced 2, 38	Normal Wear	-
	8	24	White Water	-	-	-	Replaced 10, 17	Normal Wear	8-61
	9	24	White Water	-	-	-	Replaced - 28	Preventive Maintenance	5-60
	10	16	Clarified Coal Wash Water	0	Never	5	Replaced 5,10,17,25,29 49	Acid content of water got too high.	-
IV	1	-	-	-	-	-	Replaced 1,21,22,2,23, 24,5,10,17	Worn out	3-58
	2	8	Water	0	On Occasion	15	Replaced - 38	Worn out	10-62
	3	24	Water	0	On Occasion	15	Replaced - 38	Worn out	10-62
	4	24	Water	0	On Occasion	15	Replaced - 38	Worn out	10-62
	5	8	Water	0	On Occasion	15	Replaced - 38	Worn out	10-62
	6	4	Water	10	On Occasion	5	None	None	8-56

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
IV cont.	7	24	Water	0	On Occasion	15	Replaced - 38	Worn out	10-62
	8	8	Water	0	On Occasion	15	Replaced - 38	Worn out	10-62
	9	-	-	-	-	-	Replaced 1,2,6,24,5,21, 22,23	Worn out	12-60
							Replaced - 24	Worn out	3-61
	10	8	Oil	0	On Occasion	5	Replaced 24,5,1,2,3,4, 10,17,23	Worn out	7-58
	11	8	Oil	0	On Occasion	5	Replaced - 38	Worn out	6-60
	12	-	-	-	-	-	Replaced 5,25,1,2,37,10 17,23	Worn out	5-58
	13	-	-	-	-	-	Replaced - 24,25	Worn out	4-57
V	1	4	Sea Water	-	-	-	-	-	-
	2	4	Sea Water	-	-	-	Replaced 10,17,2,5,20, 37	Worn out	5-59
							Replaced 2,10,17,5,25	Worn out	10-61
	3	4	Sea Water	-	-	-	Replaced 16,17	Worn out	6-60
							Replaced 1, 2	Worn out	8-60
							Replaced 28,5,10,17	Worn out	12-60
							Replaced 1, 2	Worn out	6-61
							Replaced 1,2,6,25	Worn out	12-61

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont.	4	4	Sea Water	-	-	-	Replaced 10,17,9,16,5, 25	Worn out	10-58
	5	4	Sea Water	-	-	-	Replaced 2,10,17,25	Worn out	6-58
							Replaced 10,17,2,37	Worn out	3-59
							Replaced 10,17	Worn out	2-60
							Replaced 10,17,7,14,8, 15,9,16	Worn out	2-61
							Replaced 1,6,25,2,3,4, 10,17,9,16	Worn out	12-61
	6	4	Sea Water	-	-	-	Replaced 10,17,2,25	Worn out	8-61
	7	4	Sea Water	-	-	-	Replaced 5,25,10,17	Worn out	1-57
							Replaced 9,10	Worn out	9-58
							Replaced 10,17,2,5	Worn out	7-59
							Replaced 10,17	Worn out	6-60
	8	4	Sea Water	-	-	-	Replaced 17	Worn out	10-56
							Replaced 10,17,2,5,20, 22	Worn out	8-59
							Replaced 10,17,2,25,22	Worn out	9-59
	9	4	Sea Water	-	-	-	Replaced 5	Worn out	4-56
							Replaced 5,10,17	Worn out	6-61
	10	4	Sea Water	-	-	-	Replaced 25, 5	Worn out	4-56
							Replaced 10,17,2,37	Worn out	11-58
							Replaced 10,17	Worn out	5-60
							Replaced 10,17,7,14,9,16	Worn out	2-61
							Replaced 10,17,25	Worn out	7-62

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont.	11	4	Sea Water	-	-	-	Replaced 10,17,2,25,37	Worn out	4-59
							Replaced 10,17,2,25,5, 20	Worn out	5-59
							Replaced 10,17	Worn out	6-60
							Replaced 6,25,10,12,9, 16	Worn out	12-61
							Replaced 1,2,25,5	Worn out	10-62
	12	4	Sea Water	-	-	-	Replaced 10,17,2,5,37	Worn out	4-59
							Replaced 1,10,17,25	Worn out	1-61
							Replaced 25, 2	Worn out	6-61
	13	4	Sea Water	-	-	-	Replaced 10,17,9,16,5, 25,7,14,3	Worn out	2-62
	14	4	Salt Water and Sand	10	Frequently	over 35	Replaced 38	Preventive Maint.	1-58
							Replaced 38	Preventive Maint.	3-59
							Replaced 38	Preventive Maint.	6-61
							Replaced 38	Preventive Maint.	9-61
							Replaced 38	Preventive Maint.	1-62
							Replaced 1 and 38	Shaft Broke	3-62
							Replaced 2,5,10,17,25	Bearings Froze	8-62
	15	4	Salt Water & Sand	10	Frequently	over	Replaced 2,10,17,25 and machined 5,29,30	Excessive Wear	9-59
							Replaced 2,5,10,17,25	Noisy	5-60
							Replaced 2,5,10,17,25	Preventive Maint.	1-61
							Replaced 5,10,17,25	Normal Overhaul	3-62

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont.	16	4	Salt Water & Sand	10	Frequently	over 35	Replaced 5,10,17,24,25	Damage due to running in reverse	4-27-60
							Complete overhaul	Preventive Maint.	9-62
	17	4	Salt Water & Sand	10	Frequently	over	Replaced 38	Preventive Maint.	1-58
							Replaced 38	Preventive Maint.	3-59
							Replaced 38	Preventive Maint.	7-61
							Replaced 38	Preventive Maint.	8-61
							Replaced 38	Preventive Maint.	7-62
	18	4	Salt Water & Sand	10	Frequently	over 35	Replaced 38	Preventive Maint.	1-58
							Replaced 2,10,17,38	Preventive Maint.	2-59
							Replaced 1,2,5,10,17,38	Shaft Broke	2-60
							Replaced 32	Maintenance Check	5-61
							Replaced 38	Maintenance Check	2-62
	19	4	Salt Water & Sand	10	Frequently	over 35	Replaced 38	Preventive Maintenance	1-58
							Replaced 38	Preventive Maint.	2-62
							Replaced 10, 17	Preventive Maint.	10-61
	20	4	Salt Water & Sand	10	Frequently	over 35	Replaced 38	Preventive Maint.	1-58
							Replaced 38	Preventive Maint.	1-62
							Replaced 2	Preventive Maint.	3-59
							Replaced 2,5,10,17,38	Preventive Maint	2-60
							Replaced 2,5,32	Preventive Maint.	3-61

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont.	21	4	Salt Water & Sand	10	Frequently	over 35	Replaced 38	Preventive Maint.	1-58
							Replaced 38	Preventive Maint.	9-61
							Replaced 38	Preventive Maint.	2-62
							Replaced 1,2,10,17,38	Preventive Maint.	11-59
							Replaced 1,2,3,4,5,10, 17,21,22	Bearings Froze due to breakage	8-62
	22	4	Salt Water & Sand	10	Frequently	over 35	Replaced 38	Preventive Maint.	1-58
							Replaced 38	Preventive Maint.	2-59
							Replaced 38	Preventive Maint.	2-62
							Replaced 10, 17	Preventive Maint.	2-59
							Replaced 2,10,17,38	Preventive Maint.	11-61
							Checked 2	Inspection	12-61
							Overhauled	Preventive Maint.	9-62
	23	4	Salt Water & Sand	10	Frequently	over 35	Replaced 38	Preventive Maint.	1-58
							Replaced 38	Preventive Maint.	8-62
							Replaced 1,2,5,10,17	Water & grit in bearings	2-60
							Replaced 2,10,17	Preventive Maint.	8-62
	24	4	Salt Water & Sand	10	Frequently	over 35	Replaced 38	Normal Maint.	1-58
							Replaced 2,5,10,17,38	Normal Maint.	1-60
							Replaced 2,10,12,13,17 18,19,25,38	Normal Maint.	1-62
	25	4	Salt Water & Sand	10	Frequently	over 35	Replaced 38	Preventive Maint.	1-58

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont.	26	8	Salt Water	5	Never	35	Replaced 5,25,10,17,2	Worn out	5-60
							Replaced 10,17,2	Worn out	10-61
							Replaced 10,17	Worn out	2-62
	27	8	Salt Water	5	Never	35	Replaced 10,17,1	Breakage	9-56
							Replaced 37	Worn out	10-56
							Replaced 10,17	Worn out	10-56
							Replaced 10,17,2,25,5	Worn out	8-60
	28	8	Salt Water	5	Never	35	Replaced 37	Corrosion	11-56
							Replaced 5,25,10,17,2	Worn out	5-60
							Replaced 5,25,10	Worn out	2-60
							Replaced 10,17,5,24,25, 1,2,3,4,7,14	Worn out	8-60
							Replaced 25,10,17	Worn out	2-61
	29	8	Salt Water	0	Never	-	Replaced 37	Worn out	10-56
							Replaced 5,25,10,17,2	Worn out	3-60
	30	8	Sea Water	5	-	35	Replaced 5,25,17,2	Worn out	7-60
							Replaced 37,5,25,10,17	Worn out	12-60
							Replaced 10,17	Worn out	3-62
	31	8	Sea Water	5	-	35	Replaced 37	Worn out	12-56
							Replaced 5,25,10,17,2	Worn out	5-60
							Replaced 22,10	Worn out	12-61
	32	8	Sea Water	5	-	35	Replaced 2,5,10,17,8,15	Worn out	2-59
							Replaced 5,25,10,17,2	Worn out	3-60
							Replaced 1,2,3,4,10,17, 25	Worn out	10-60

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont.	33	8	Sea Water	5	-	35	Replaced 5,25,10,17,2	Worn out	5-60
	34	8	Sea Water	5	-	35	Replaced 5,25,10,17,2	Worn out	3-60
	35	8	Sea Water	5	-	35	Replaced 1,2,10,17	Worn out	7-56
							Replaced 5,25,10,17,2	Worn out	5-60
							Replaced 10,17,5,25	Worn out	10-61
	36	8	Sea Water	5	Never	-	Replaced 2,10,17	Worn out	8-56
							Replaced 37	Worn out	10-56
							Replaced 5,25,1,2,3,4,	Worn out	12-59
							Replaced 10,17,2,25	Worn out	11-61
							Replaced 10,17,3,4	Worn out	3-62
	37	8	Sea Water	5	-	35	Replaced 37	Worn out	10-56
							Replaced 5,25,10,17	Worn out	10-59
							Replaced 1,2,10,17,5,25	Worn out	10-61
							Replaced 10,17,2,25	Worn out	11-61
	38	8	Sea Water	5	-	35	Replaced 5,25	Worn out	1-57
	39	2	Sea Water	10	Never	5	Replaced 5,25	Excessive Clearance	10-58
							Replaced 10,12,17,18	Excessive Wear	8-60
							Replaced 2,5,10,17	Excessive Wear	4-61
							Replaced 2,10,12,17,18	Excessive Wear	1-62
							Replaced 6,10,17	Damage during operation and maintenance	6-62

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont.	40	2	Sea Water	10	Never	5	Replaced 38	Worn	4-60
							Replaced 1, 10, 17, 38	Shaft twisted off	7-62
	41	2	Sea Water	10	Never	5	Replaced 2,38	Excessive Wear	10-60
							Replaced 38	Worn	4-61
							Replaced 10,17,25	Worn	2-62
	42	2	Sea Water	10	Never	5	Replaced 10,12,17,18	Excessive Wear	11-59
							Replaced 2,3,4,10,17	Excessive Wear	6-60
							Replaced 10	Excessive Wear	12-61
							Replaced 2,3,4,5,10,17	Excessive Wear	8-62
	43	2	Sea Water	10	Never	5	Replaced 2,5	Excessive Clearance	8-60
							Replaced 10,17	Excessive Wear	10-60
							Replaced 2,3,4,10,17	Excessive Wear	9-61
							Replaced 10,17	Excessive Wear	5-62
	44	2	Sea Water	10	Never	5	Replaced 2,10,17	Excessive Wear	10-60
							Replaced 10,17,24,25	Excessive Wear	2-62
	45	2	Sea Water	10	Never	5	-	-	-
	46	2	Sea Water	10	Never	5	Replaced 10,17	Running hot	6-59
							Replaced 1	Bent	7-59
							Replaced 10,17	Running Hot	2-60
							Replaced 2	Worn	10-61

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V Cont.	47	2	Sea Water	10	Never	5	Replaced 10,17	Running Hot	2-60
							Replaced 10,17	Running Hot	11-61
	48	2	Sea Water	10	Never	5	Replaced 5,10,17,25	Excessive Clearance	3-60
							Replaced 10,17,25	Excessive Wear	8-60
							Replaced 2,5,10,17	Excessive Wear	12-60
							Replaced 2,10	Excessive W ar	6-61
							Replaced 17,22	22 corroded	6-61
	49	2	Sea Water	10	Never	5	Replaced 1,2,10,17	Shaft Broken	6-62
	50	2	Sea Water	10	Never	5	Replaced 5,10,17	Excessive Wear	9-61
							Replaced 10,17	Excessive Wear	4-62
	51	2	Sea Water	10	Never	5	Replaced 2	Excessive Wear	2-59
							Replaced 10,17	Excessive Clearance	12-59
							Replaced 2,5,10,17	Excessive Wear	3-61
							Replaced 25	Excessive Wear	8-62
	52	8	Sea Water	5	Never	35	Replaced 41	Broken	8-62
	53	8	Sea Water	5	Never	35	Replaced 5,10,17,2	Worn out	4-62
	54	8	Sea Water	5	Never	35	-	-	-

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont.	55	8	Sea Water	5	Never	35	Replaced 2,10,17,5	Worn out	3-62
	56	8	Sea Water	5	Never	35	-	-	-
	57	8	Sea Water	5	Never	35	Replaced 10,17,3,4,2, 41	Worn out	6-62
	58	8	Sea Water	5	Never	35	Replaced 10,17,41	Worn out	7-62
	59	8	Sea Water	5	Never	35	Replaced 1,2,8,15,10, 17,41	Worn out	5-62
	60	8	Sea Water	5	Never	35	-	-	-
	61	8	Sea Water	5	Never	35	Replaced 5,25	Worn out	5-62
	62	8	Sea Water	5	Never	35	-	-	-
	63	8	Sea Water	5	Never	35	None		6-62
	64	8	Sea Water	5	Never	35	None		5-62
	65	8	Sea Water	10	-	-	-	-	-

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont	66	8	Sea Water	10	-	-	Replaced 10,17	Bearings corroded due to salt entering in them.	8-62
							Replaced 10	Burr on bearing	8-62
	67	4	Sea Water	10	-	-	-	-	-
	68	8	Sea Water	10	-	-	Replaced 1,2,3,4,10,17, 7	Burned up due to over lubrication	8-62
	69	4	Sea Water	10	-	-	-	-	-
	70	16	Sea Water	10	-	-	-	-	-
	71	8	Sea	10	-	-	Replaced 1,10,17,24,25	Impeller cracked and bearings scored	9-61
							Replaced 10,17	Excessive wear	5-62
	72	16	Sea Water	10	-	-	Replaced 27,5,10,11,25	Burr on bearing and packing cut sleeves	10-62
	73	12	Sea Water	10	-	-	-	-	-

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont	74	4	Sea Water	10	-	-	Replaced 24,25	Excessive clearance	6-62
	75	4	Sea Water	10	-	-	-	-	-
	76	16	Sea Water	10	-	-	Replaced 1,2,5,10,17 25	Shaft broke - pump rotating backward	8-62
	77	8	Sea Water	8	-	-	Replaced 2,10	Packing cut sleeves	5-62
							Replaced 10,17,22	Bearings corroded, key sheared off	7-62
	78	24	Sea Water	5	Frequently	-	Replaced 1,2,3,4	Worn out	5-62
	79	24	Sea Water	5	Frequently	-	Replaced 10,17,5	Worn out	5-62
	80	24	Sea Water	5	Frequently	-	Replaced 5 Replaced 5,25	Worn out Worn out	11-61 8-62
	81	24	Sea Water	5	Frequently	-	Replaced 5	Worn out	6-62
	82	24	Sea Water	5	Frequently	-	Replaced 2,5	Worn out	5-62

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
V cont	83	24	Sea Water	5	Frequently	-	Replaced 2,5,10,17	Worn out	5-62
	84	24	Sea Water	5	Frequently	-	Replaced 1,2,10,5	Worn out	5-62
	85	24	Sea Water	5	Frequently	-	-	-	-
	86	24	Sea Water	5	Frequently	-	Replaced 2,5,10,17	Worn out	5-62
	87	24	Sea Water	5	Frequently	-	Replaced 2,5,10,17	Worn out	6-62
	88	24	Sea Water	5	Frequently	-	-	-	-
	89	24	Sea Water	5	Frequently	-	-	-	-
	90	24	Sea Water	5	Frequently	-	Replaced 2,5,10,17	Worn out	6-62
VI	1	2	Fresh Water	0	Never	-	Replaced 10 Replaced 5,25 Checked 24 and 25 Overhauled	Over lubrication Failed Inspection Preventive Maintenance	7-56 10-56 9-60 12-61
	2	2	Fresh Water	0	Never	-	Checked 24 and 25 Overhauled	Inspection Preventive Maint.	9-60 12-61

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
VI cont.	3	2	Fresh Water	0	Never	-	Checked 24 and 25 Overhauled	Inspection Preventive Maint.	9-60 12-61
	4	2	Fresh Water	0	Never	-	Checked 24 and 25 Overhauled	Inspection Preventive Maint.	9-60 12-61
	5	2	Fresh Water	0	Never	-	Check 24 and 25 Overhauled	Inspection Preventive Maint.	9-60 12-61
	6	2	Fresh Water	0	Never	-	Checked 24 and 25 Overhauled	Inspection Preventive Maint.	9-60 12-61
	7	2	Fresh Water	0	Never	-	Check 24 and 25 Overhauled	Inspection Preventive Maint.	9-60 9-61
	8	2	Fresh Water	0	Never	-	Checked 24 and 25 Overhauled	Inspection Preventive Maint.	9-60 9-61
	9	2	Water	5	Frequently	5	Overhauled Checked & polished 1 & replaced 2,3,4,5,6, 10,12,13,17,18,19,24, 25,26,27,38,47,52,53	Preventive Maint. Preventive Maint.	1-59 7-62
	10	2	Water	5	Frequently	5	Overhauled Checked and polished 1, replaced 2,3,4,5,6,10, 12,13,17,18,19,24,25, 26,27,38,47,52,53	Preventive Maint. Preventive Maint.	1-62 9-62
	11	2	Water	5	Frequently	5	Overhauled Checked & polished 1	Preventive Maint. Preventive Maint.	1-59 9-62

(cont. next page)

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
VI cont	11 cont.						Replaced 2,3,4,5,6,10, 12,13,17,18,19,24,25, 26,27,38,47,52,53	Preventive Maint.	9-62
	12	2	Water	5	Frequently	5	Overhauled Checked and polished 1, replaced 2,3,4,5,6,10, 12,13,17,18,19,24,25, 26,27,38,47,52,53	Preventive Maint. Preventive Maint.	1-59 7-62
	13	2	Water	5	Frequently	5	Overhauled Checked and polished 1, Replaced 2,3,4,5,6,10, 12,13,17,18,19,24,25, 26,27,38,47,52,53	Preventive Maint. Preventive Maint.	1-59 7-62
	14	2	Water	5	Frequently	5	Overhauled Checked and polished 1, Replaced 2,3,4,5,6,10, 12,13,17,18,19,24,25, 26,27,38,47,52,53	Preventive Maint. Preventive Maint.	1-59 7-62
	15	2	Water	5	Frequently	5	Overhauled Checked and polished 1, Replaced 2,3,4,5,6,10, 12,13,17,18,19,24,25, 26,27,38,47,52,53	Preventive Maint. Preventive Maint.	1-59 7-62
	16	2	Water	5	Frequently	5	Overhauled Checked and polished 1 Replaced 2,3,4,5,6,10,12, 13,17,18,19,24,25,26,27, 38,47,52,53.	Preventive Maint. Preventive Maint.	1-59 7-62

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
VII	1	12	Clear Water	0	Nver	5	-	-	-
	2	12	Clear Water	0	Never	5	-	-	-
	3	24	Water	0	Never	-	-	-	-
	4	-	-	-	-	-	Replaced 24,25 Replaced 24,25	Breakdown Breakdown	8-58 10-58
	5	16	Water (Domestic Use)	0	Never	0	-	-	-
	6	24	Pond Water	0	Never	5	-	-	-
	7	24	Cold Raw Water	10	Frequently	over 35	-	-	-
	8	16	Gaso-line	0	On Occasion	5	Replaced 1,10,17	Poor Alignment	5-62
	9	4	Distil-led Water	0	Never	5	-	-	-
	10	4	Dist. Water	0	Never	5	-	-	-

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
VII cont.	11	4	Dist. Water	0	Never	5	-	-	-
	12	-	-	-	-	-	Replaced 2,3,4,5,6,22, 23,24,25,32,34,38,50	Breakdown	5-62
	13	8	Water	-	-	-	-	-	-
	14	12	Clear Water	5	Never	5	-	-	-
	15	4	Water	0	Never	5	Replaced 2,5,10,17,38	Faulty Bearing	1-60
	16	16	-	-	-	-	-	-	-
	17	12	Filtered Water	-	On Occasion	-	-	-	-
	18	24	Ground Water	5	Never	15	Replaced 25,28	Operation very close to shut-off	6-61
	19	4	Wash Water	5	On Occasion	15	-	-	-
	20	24	Irrigation Water	5	Frequently	35	-	-	-

FIELD REPAIR AND MAINTENANCE DATA

Group No.	Pump No.	Hours Per Day	Type of Fluid	Percentage Impurities	Operation Near Shutoff	Percentage Variation From Rating	Maintenance Action	Reason for Maintenance	Date
VIII	1	4	Water	0	Never	35	None	-	2-58
	2	4	Water	5	-	35	Replaced 41	Broken	11-61
	3	16	Water	0	On Occasion	5	None	None	1-59
	4	24	Water	0	Frequently	35	None	None	3-61
	5	16	Water	0	Frequently	35	Replaced 1 Replaced 1	Broken Broken	11-61 9-62
	6	4	Water	0	Never	5	None	None	4-60
	7	16	Water	0	Never	5	None	None	8-60
	8	24	Brine	+5	Never	15	Replaced 28 Replaced 10,17	Worn out Worn out	3-61 5-61
	9	24	Brine	+5	Never	15	None	None	2-61
	10	24	Brine	+5	Never	15	None	None	2-61
	11	24	Water	0	Frequently	35	None	None	5-62
	12	16	Water	0	Frequently	35	None	None	7-61
	13	24	Water	5	On Occasion	15	None	None	5-62
	14	24	Water	0	On Occasion	5	Replaced 24	Worn out	8-62